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# 3D simulations of an injection test done into an unsaturated porous and fractured limestone

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## Issues

- growing concern about environmental protection on issues such as the stability of rocky slopes or the sealing of underground storage sites
- both in situ measurements and model developments are needed to fully understand and predict the risks of instability and/or the fluid flow pattern into the rock mass

## Context

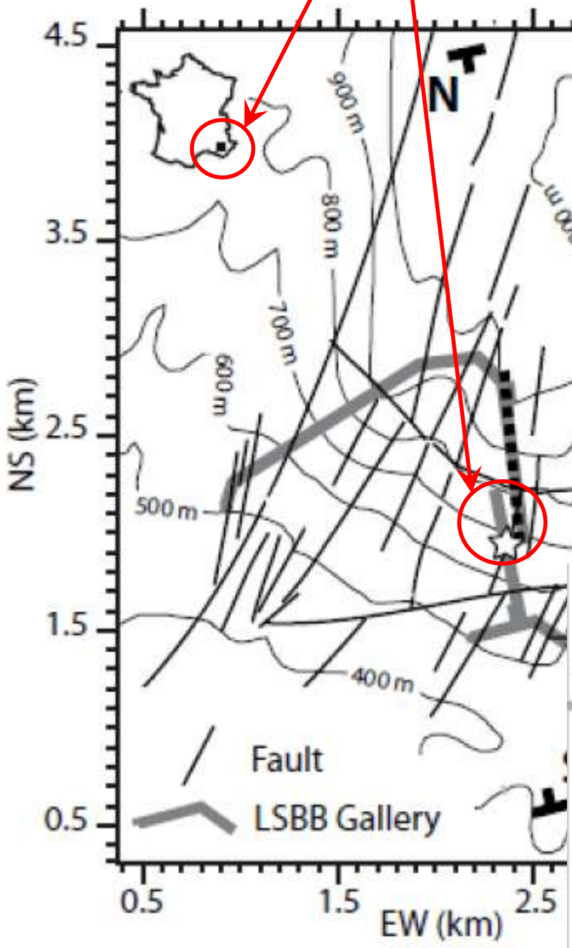
- french research program called $HPPP_{CO2}$ founded by ANR. The overall objective of the program is to develop tools and methods to characterize porous and fractured rock environments
- this program focuses on experiments conducted at the LSBB site (Laboratoire Souterrain à Bas Bruit – Low Noise Underground Laboratory) located close to Apt, Vaucluse, France

## Objectives of our contribution

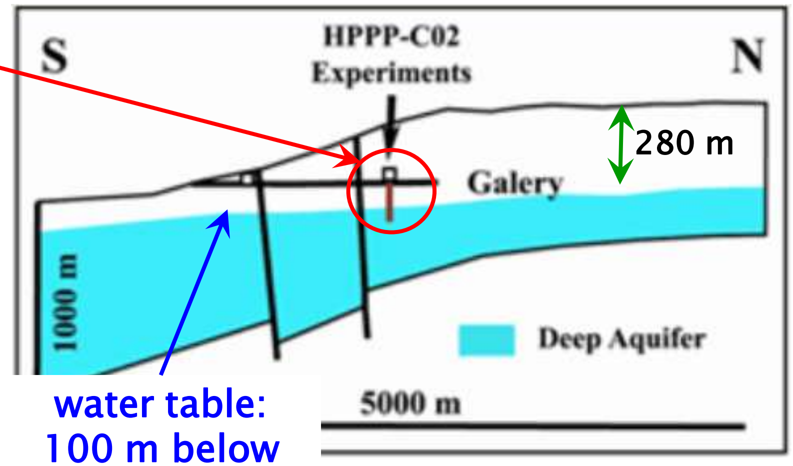
- to develop numerical model to represent the effect of injection test in unsaturated porous and fractured rock mass
- to derive the rock-mass characteristics from numerical simulations of the in situ tests done during the program

# Site description

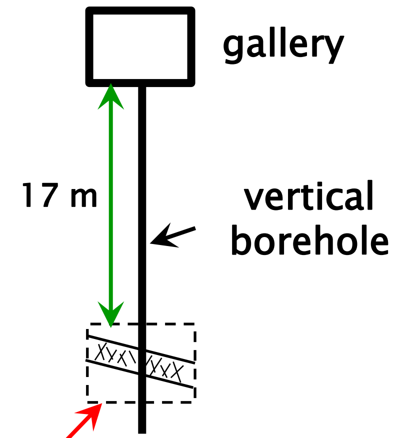
Location of site into the LSBB gallery



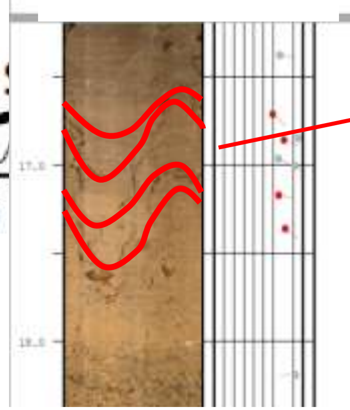

Gallery drilled into unsaturated limestone



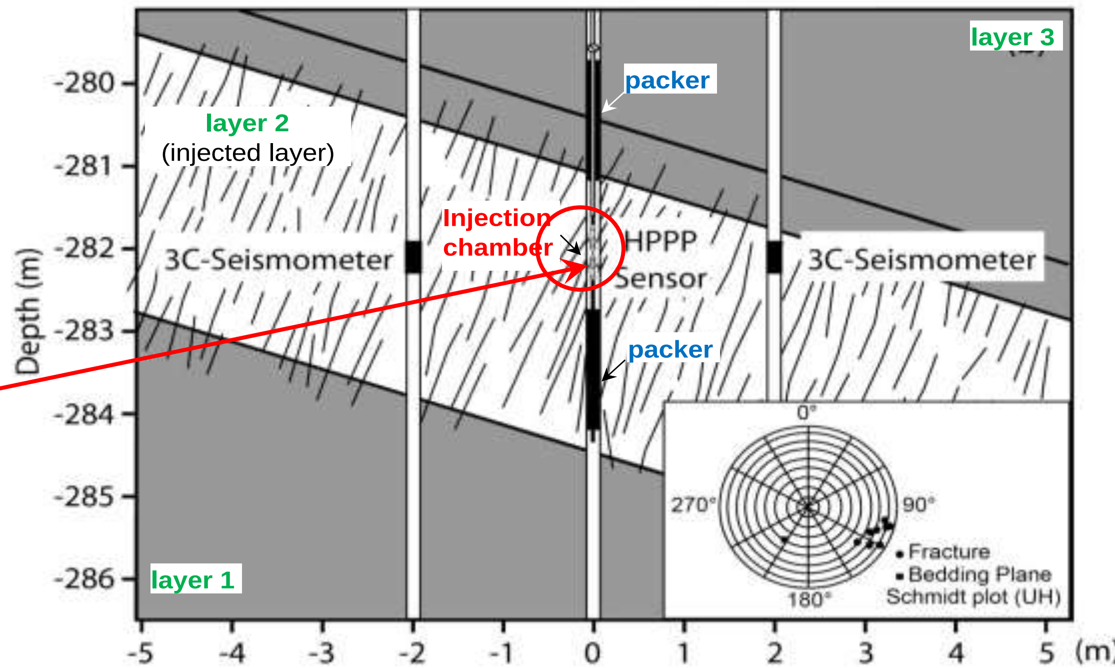

water table: 100 m below the gallery




Fracture traces around the borehole



Zoom of the injection zone

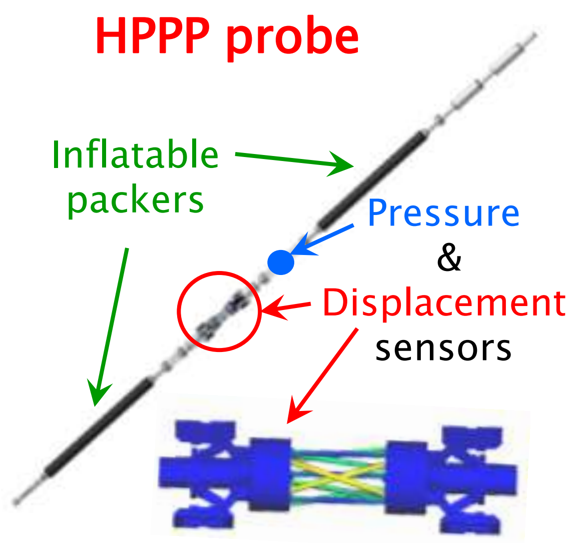


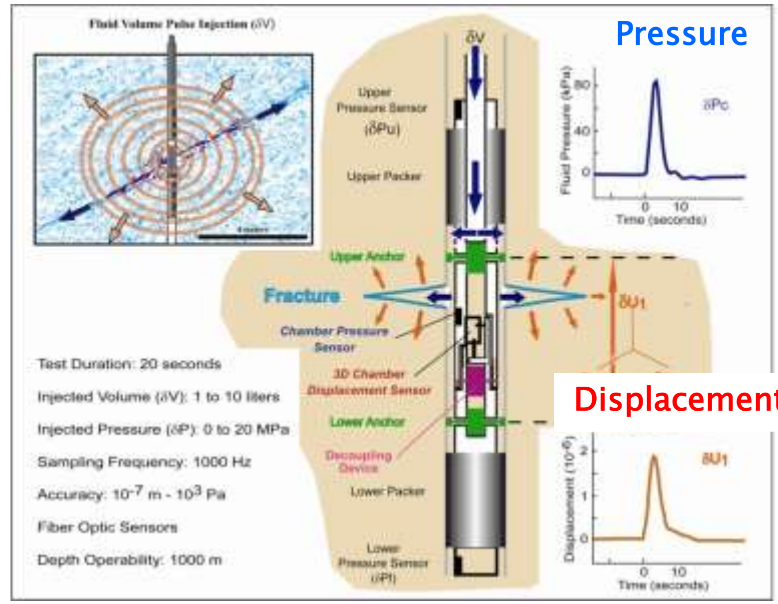
# Measurements done during the injection test

- The **HPPP probe** allows high frequency (1000 Hz) & accurate measurements (0.1mm ; 0.01 atm)

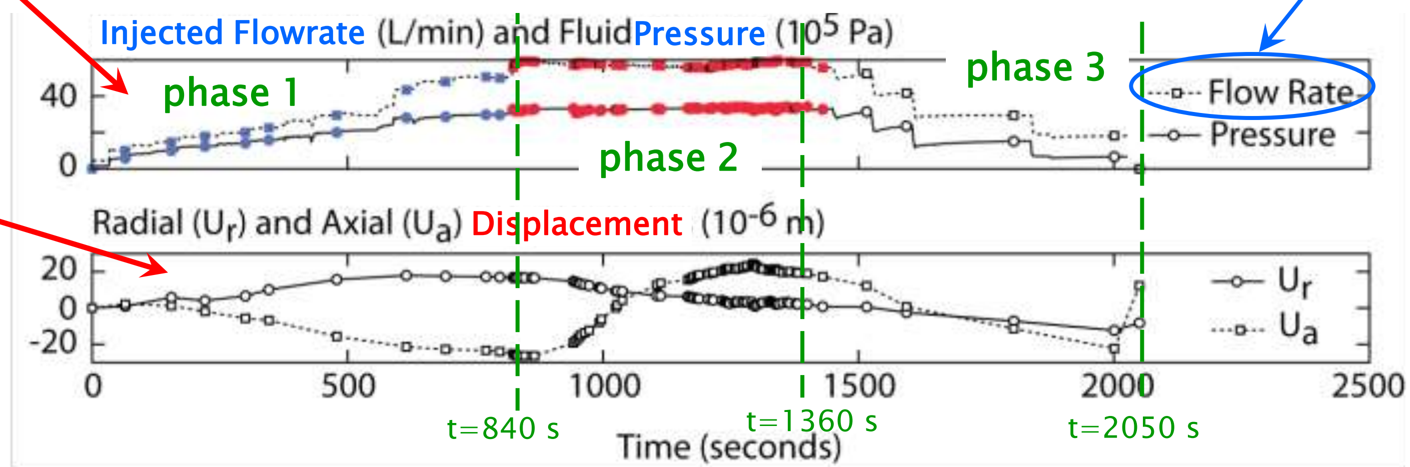
- **3 injection test phases:** (1) $Q_{inj}$ and $P_{water}$ reach progressively their max. values: 59 ℓ/mn and 35 atm ; (2) they are maintained constant ; (3) then gradually decreased

- change in $P_{water}$ induced mechanical displacement (Ur and Ua) due to the rockmass strain and to fracture opening and shear (max. about 30 μm)



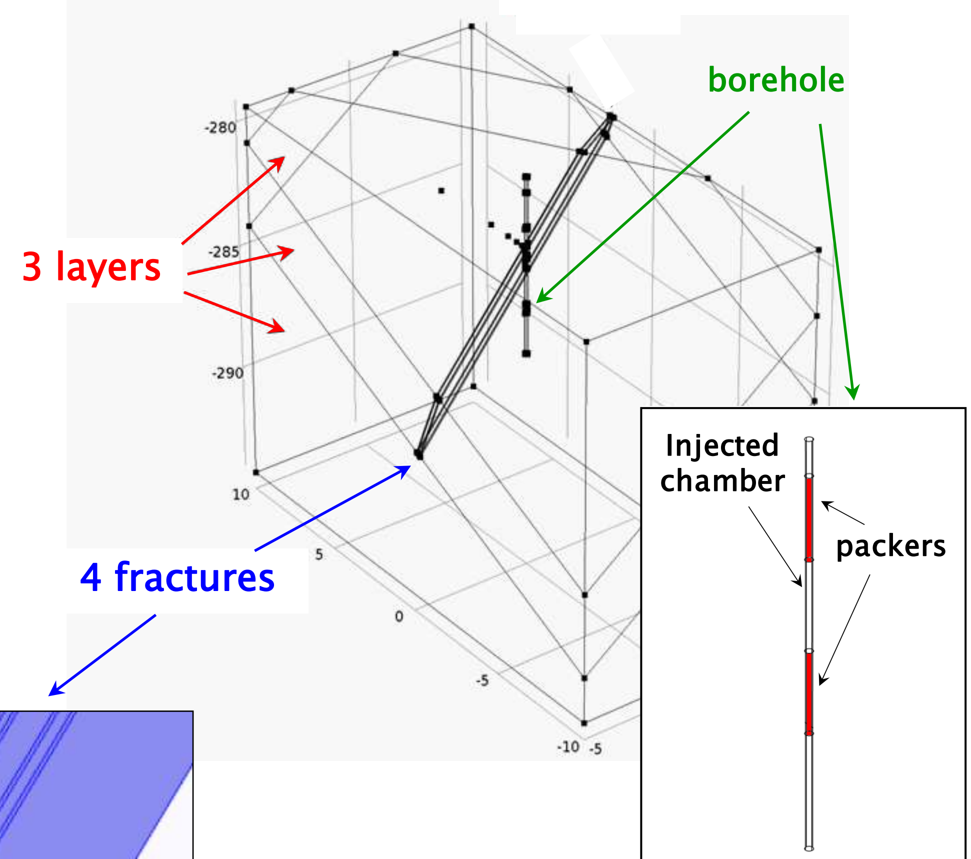

Injected Flowrate

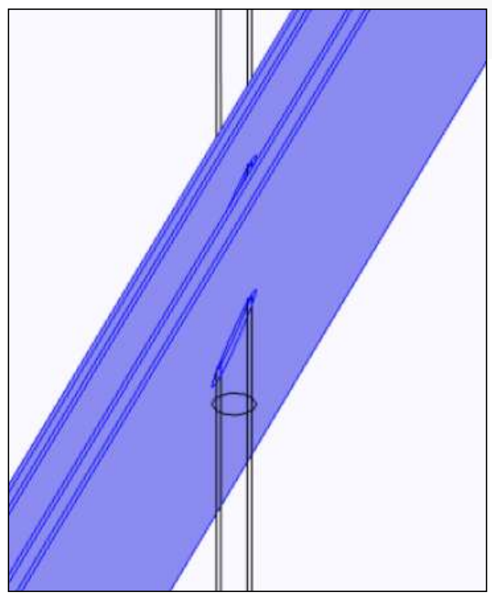


# Model set-up

## Main assumptions

- 3D geometry around the injected zone (included 3 layers)
- 4 fractures included as equivalent porous tabular zones
- unsaturated porous rock mass (two phase flow considering van Genuchen relations)
- hydro-mechanical coupling
- mechanical constitutive law: elastic & elasto-plastic (DP)



## Modeling phases

1) before borehole drilling
2) borehole drilling
3) packer inflating
4) injection test

Fracture ($K_n$, $K_s$, $a_0$) => Porous tabular zone with eq. HM properties (e, $E_1$,$E_3$,…, $k_{tabular}$):

$E_3 = e\ K_n$ $\qquad E_1 = 1\ K_s$

$G_{13} = E_1\ E_3 / (E_1 + E_3)$

$k_{tabular} = a_0^3 / 12e$

# Fluid and rockmass properties (reference case)

## For the fluids:

- $\rho_{water}$ = 1000 kg/m$^3$ ; $\mu_{water}$ = $10^{-3}$ Pa.s ; $K_{water}$ = 2 $10^9$ Pa
- $\rho_{air}$ = 1.28 kg/m$^3$ ; $\mu_{air}$ = 1.81 $10^{-5}$ Pa.s ; $K_{air}$ = 1.41 $10^5$ Pa

## For the rock mass:

- $\rho_R$ (saturated density) = 2650 kg/m$^3$
- $E_u$ (undrained Young modulus) = 25 MPa (10 GPa for layer 2)
- $\nu_u$ (undrained Poisson ratio) = 0.25
- $K_i$ (intrinsic perméability) = 2.$10^{-14}$ ($10^{-13}$ m$^2$ for layer 2)
- $\phi_{tot}$ (total porosity) = 0.20
- $\phi_{res}$ (residual porosity) = 0.08 (0.15 for layer 2)
- b (Biot coefficient) = 0.9
- van Genuchten parameters: a= 0.66 ; b=0.5 ; c=0.9 ; $P_0$=100000 Pa
to define $P_c$, $kr_{water}$, $kr_{air}$ (data from Lavoux limestone laboratory test)

## For the fracture:

- $K_n$ = 5 GPa/m; $K_s$ = 0.1 GPa/m; $a_0$ = 2 $10^{-4}$ => “equivalent” tabular zone:
e = 0.04 m; $E_1$ = 100 MPa; $E_3$ = 200 MPa; $G_{13}$ = 67 MPa; $k_{tabular}$ = 1.67 $10^{-11}$ m$^2$

# Description of the two-phase flow model without mechanical coupling

## Two equations to describe the water (w) and air (nw) flows:

Generalized Darcy's laws

$$\rho_w\left(S_w\frac{\partial p_w}{\partial t}+C_{p,w}\frac{\partial p_{nw}}{\partial t}\right)+\nabla.\left(-\rho_w\frac{k_i kr_w}{\mu_w}(\nabla p_w+\rho_w g\nabla z)\right)=Q_{m,w}$$

Source terms

$$\rho_{nw}\left(C_{p,w}\frac{\partial p_w}{\partial t}+S_{nw}\frac{\partial p_{nw}}{\partial t}\right)+\nabla.\left(-\rho_{nw}\frac{k_i kr_{nw}}{\mu_{nw}}(\nabla p_{nw}+\rho_{nw} g\nabla z)\right)=Q_{m,nw}$$

with:

$$S_w=-C_{p,w}+\frac{\theta_w}{K_w}\qquad S_{nw}=-C_{p,w}+\frac{\theta_{nw}}{K_{nw}}\qquad C_{p,w}=\frac{\partial\theta_w}{\partial p_c}=-\frac{\emptyset(1-sr_w)}{p_0}\frac{a}{(1-a)}se_w^{\frac{1}{a}}\left(1-se_w^{\frac{1}{a}}\right)^a$$

where:

- $\phi$ is the total porosity; $\theta_w$ and $\theta_{nw}$ are the volume fraction ($\theta_w+\theta_{nw}=\phi$)
- $Se_w$ and $Se_{nw}$ are the effective saturation ($Se_w+Se_{nw}=1$)
- $p_w$ and $p_{nw}$ are the fluid pressures ($p_c=p_{nw}-p_w$ is the capillary pressure)
- $\kappa_{int}$ is the intrinsic permeability of the porous medium [$m^2$]; $kr_w$ and $kr_{nw}$ are the relative permeabilities (defined from the well known **van Genuchten equations)**
- $\mu_w$ and $\mu_{nw}$ are the fluid's dynamic viscosities ; $\rho_w$ and $\rho_{nw}$ are the fluid densities ; $K_w$ and $K_{nw}$ are the fluid compressibilities

# Description of the hydro-mechanical model
## Single-phase flow

For a **single-phase flow**, the hydro-mechanical coupling impacts the flow equation as followed:

$$\rho_f\, S \frac{\partial p_f}{\partial t} + \nabla\left(\rho_f\,\left(-\frac{k_i}{\mu_f}(\nabla p_f + \rho_f g \nabla z)\right)\right) = -\rho_f\, b\, \frac{\partial(\epsilon_{vol})}{\partial t}$$

**with:**

$$S = \frac{\phi}{K_f} + \frac{(b-\phi)(1-b)}{K_0}$$

terms due to HM coupling

**where:** b is the Biot coefficient ; $\varepsilon_{vol}$ is the trace of the strain tensor ; $K_0$ is the drained bulk modulus of the rock mass

An additional equation has to be considered related to solid deformation under purely gravitational load **(inertial effects neglected):**

$$-\nabla.\sigma_{tot} = \rho_R.g = (\rho_R{}^0 + \phi\rho_f)g$$

**where:** $\sigma_{tot}$ is the total stress tensor ; $\rho_R$ & $\rho_R{}^0$ are the saturated & dry density

# Description of the hydro-mechanical model

## Two-phase flow

For a two-phase flow, we propose the following set of equations:

$$\rho_w \left( S_w \frac{\partial p_w}{\partial t} + C_{p,w} \frac{\partial p_{nw}}{\partial t} \right) + \nabla . \left( -\rho_w \frac{k_i kr_w}{\mu_w} (\nabla p_w + \rho_w g \nabla z) \right) = -\rho_w \; b \; \frac{\theta_w}{\phi} \frac{\partial(\epsilon_{vol})}{\partial t}$$

$$\rho_{nw} \left( C_{p,w} \frac{\partial p_w}{\partial t} + S_{nw} \frac{\partial p_{nw}}{\partial t} \right) + \nabla . \left( -\rho_{nw} \frac{k_i kr_{nw}}{\mu_{nw}} (\nabla p_{nw} + \rho_{nw} g \nabla z) \right) = -\rho_{nw} \; b \; \frac{\theta_{nw}}{\phi} \frac{\partial(\epsilon_{vol})}{\partial t}$$

with:

$$S_w = -C_{p,w} + \frac{\theta_w}{K_w} + \frac{(b - \theta_w)(1 - b)}{K_0} \qquad S_{nw} = -C_{p,w} + \frac{\theta_{nw}}{K_{nw}} + \frac{(b - \theta_{nw})(1 - b)}{K_0}$$

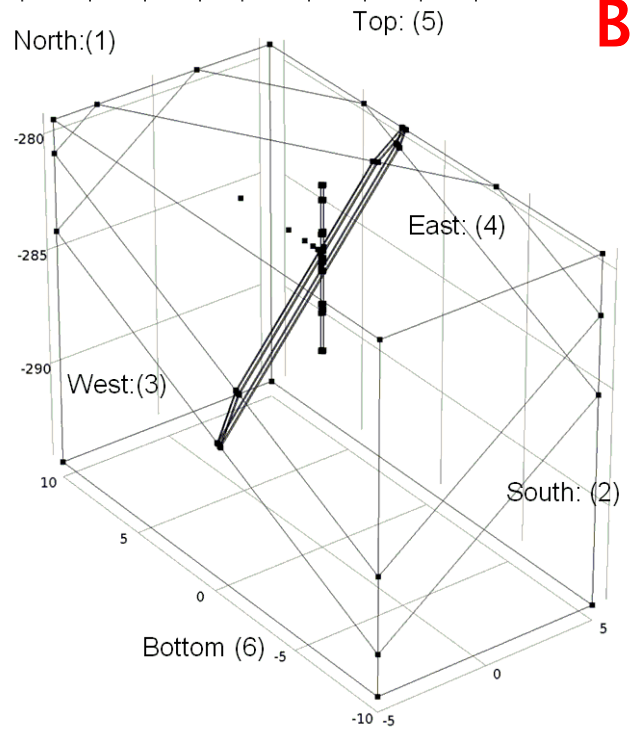
And the additional equation becomes:

$$-\nabla . \sigma_{tot} = (\rho_R{}^r) . g = (\rho_R{}^0 + \theta_w \rho_w + \theta_{nw} \rho_{nw}) . g$$

# Boundary conditions

- **top face**
  $\sigma = \rho g h$
  $P_{water} = 0.025$ MPa
  $P_{air} = 0.1$ MPa
  => $Se_w = 0.79$

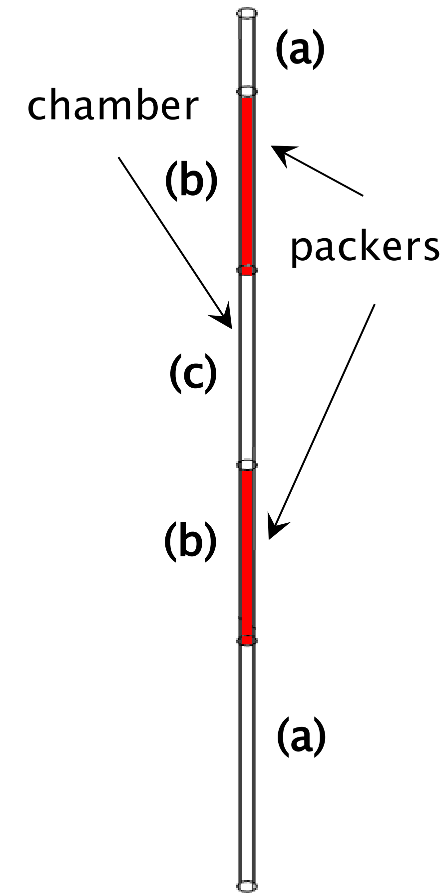
- **other faces**
  no displacement
  no (water & air) flow




- **on borehole walls**

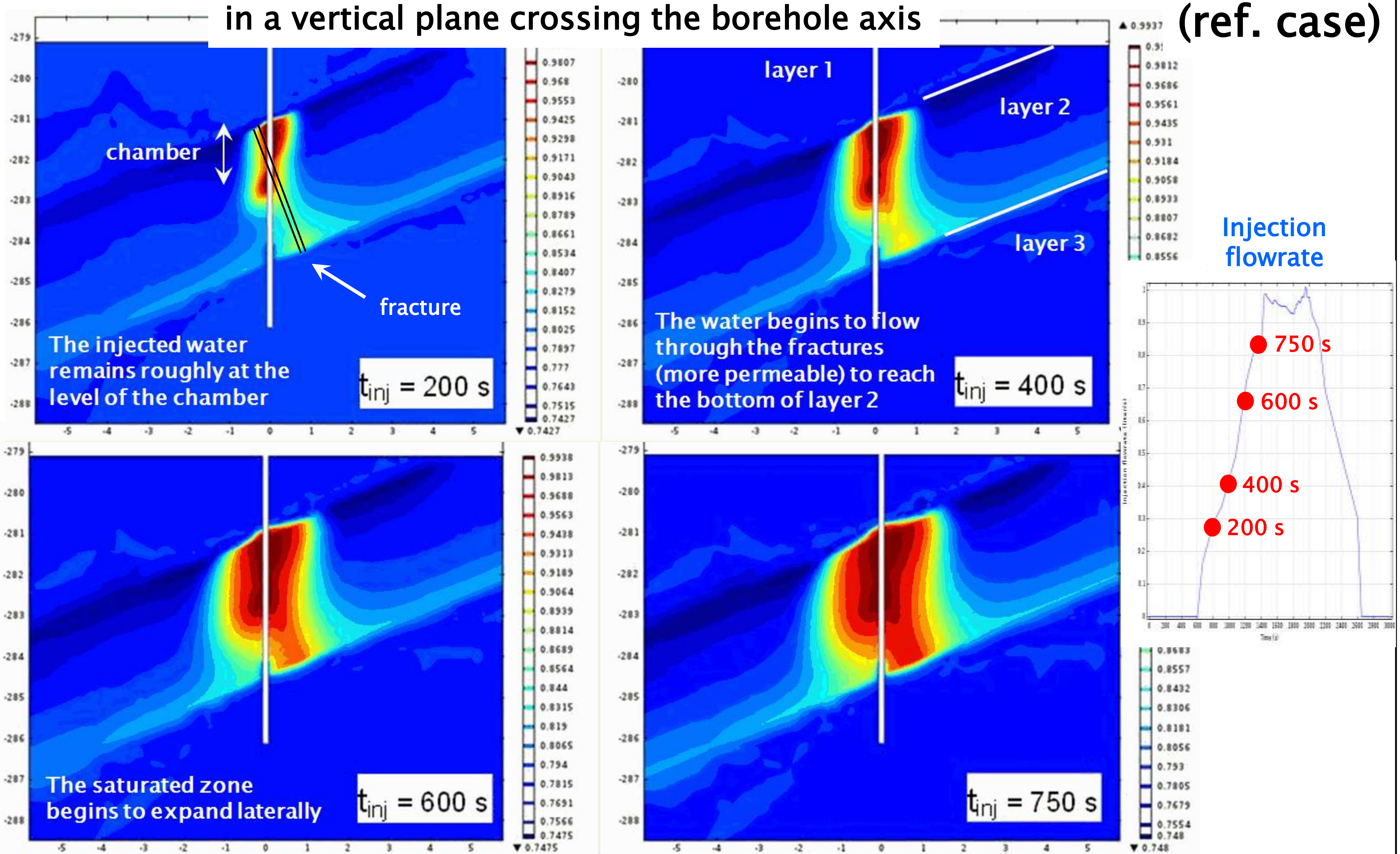
| | | Before the borehole drilling | Borehole drilling | Packer inflating | Water injection and post injection |
|---|---|---|---|---|---|
| On borehole wall | (a) naked borehole | $\sigma_r = \rho g z$<br>$P_{water} = 0.025$ MPa<br>$P_{air} = 0.1$ MPa | $\sigma_r = 0$ - $P_{water} = 0.025$ MPa – $P_{air} = 0.1$ MPa | | |
| | (b) packers | $\sigma_r = \rho g z$<br>No (water & air) flow | $\sigma_r = 0$<br>No (water & air) flow | $\sigma_r = \rho g z$<br>No (water & air) flow | |
| | (c) chamber | $\sigma_r = \rho g z$<br>No (water & air) flow | $\sigma_r = 0$<br>No (water & air) flow | | $\sigma_r = 0$<br>No air flow<br>$Q_{inj} = f(time)$ |

Injected flowrate



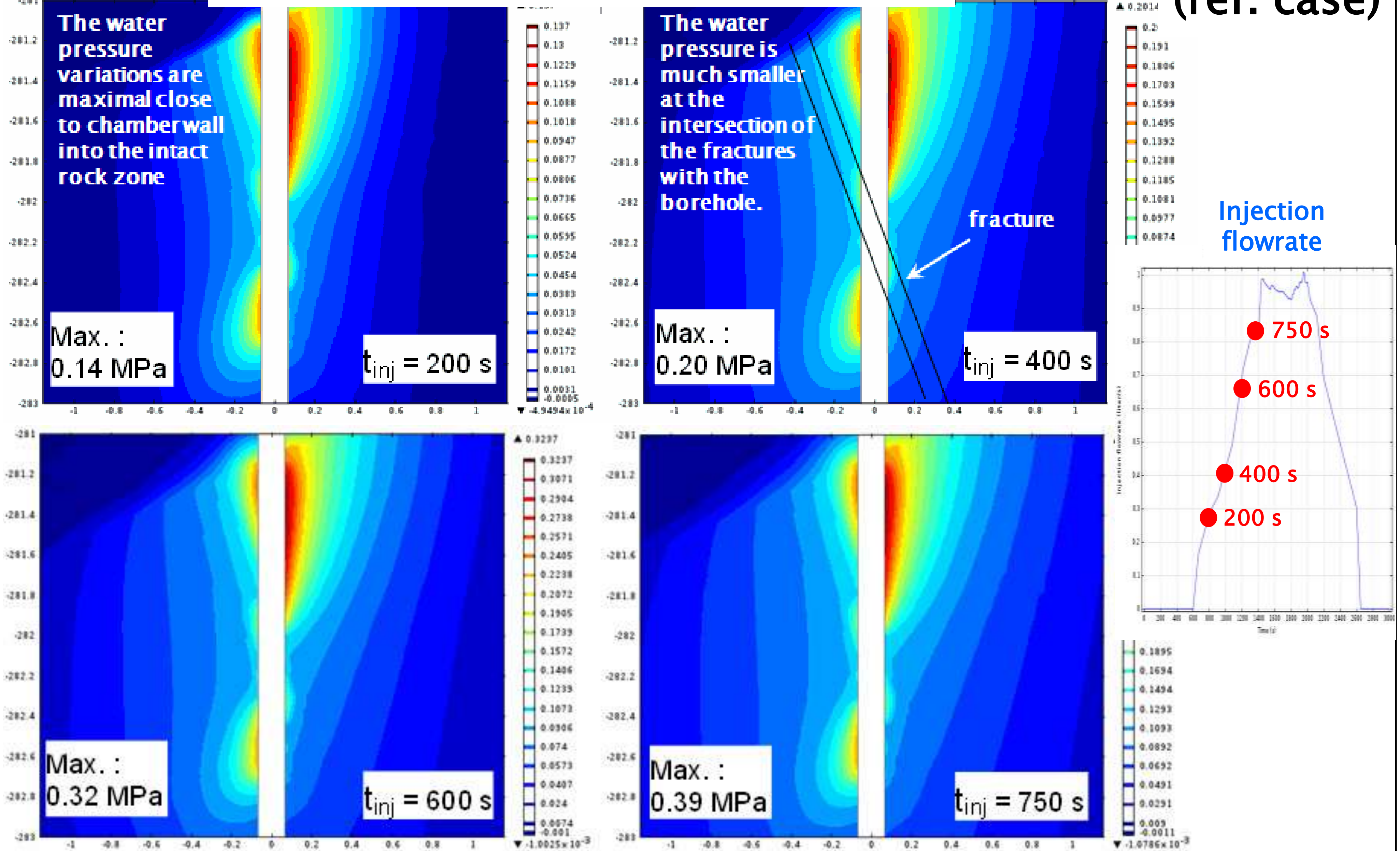
# Results (ref. case)

## Iso-values of water effective saturation in a vertical plane crossing the borehole axis



# Results (ref. case)

## Iso-values of water pressure variations in a vertical plane crossing the borehole axis



# Sensitivity studies

## … on the value of :

- **Young modulus** : 12.5 GPa to 25 GPa / 5 GPa to 10 GPa for layer 2
- **intrinsic permeability** : 2. $10^{-15}$ to 2.$10^{-14}$ $m^2$ / $10^{-14}$ to $10^{-13}$ $m^2$ for layer 2
- **fracture parameters** : $K_n$ : 2.5 to 5 GPa/m ; $K_s$ : 0.05 to 0.1 GPa/m ; $a_0$ : 0.1 to 0.5 mm

**Impact of injection on water pressure variation and water effective saturation: sensitive to the rock-mass intrinsic permeability value ($k_i$)**

$k_i$ perm: 2.$10^{-13}$ $m^2$ ↘ 5.$10^{-14}$ $m^2$

$\Delta p_w$ intact rock: 0.06 MPa ↗ 0.21 MPa

$\Delta p_w$ fracture: 0.02 MPa ↗ 0.08 MPa

sat. zone extension: 0.45 m ↗ 0.70 m

*(after 400 s of injection)*

=> **back analysis from the measurements: $k_i$ close to $10^{-14}$ $m^2$**

**Impact of injection on displacement variation: sensitive to Young modulus value (E)**

E: 10 GPa ↘ 5 GPa

Ur at borehole wall: −2.0 mm ↗ −5.5 mm

Ur 0.5 m inside the rock mass: 2.0 mm ↗ 4.0 mm

*(after 60 s of injection)*

=> **back analysis from the measurements: E close to 5 GPa**

# Concluding remarks

- A specific COMSOL model has been developed to represent the hydro-mechanical behavior of a porous and fractured rock mass in unsaturated condition

- This model has been used to simulate an in situ injection test done at LSBB site in the field of the French ANR project HPPP-CO2

- Despite some convergence problems (for low permeability cases), the result given by the 3D model allow us:

  - to underline the impact of fractures on the hydro-mechanical response of the rock-mass to water injection that leads to pressure decrease and displacement increase

  - to estimate the rock mass intrinsic permeability and compressibility of the injected layer. From the simulation done and a comparison to the measurements, we can assume: a rock-mass intrinsic permeability close to $10^{-14}$ $m^2$ and a Young's Modulus close to 5 GPa