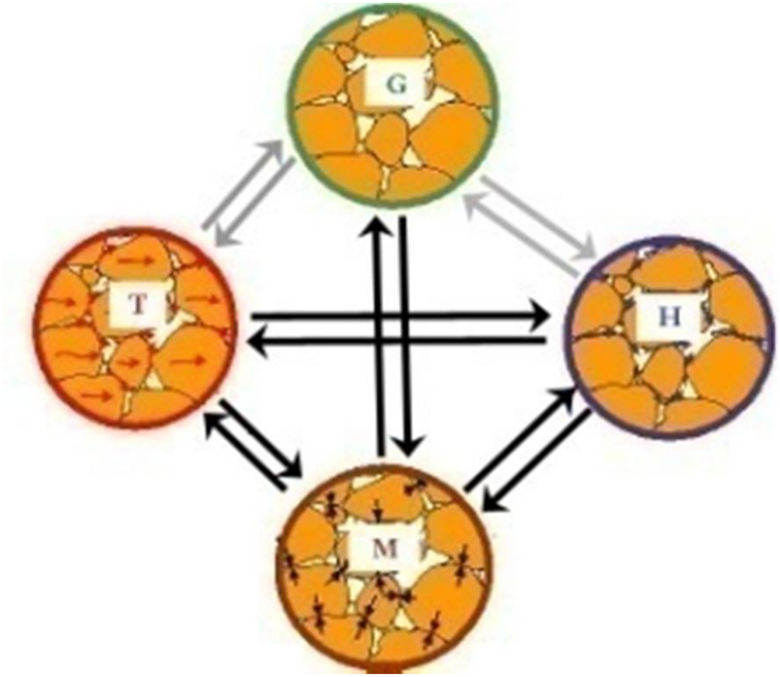
Introduction to Reservoir Geomechanics

Geochemical Coupling



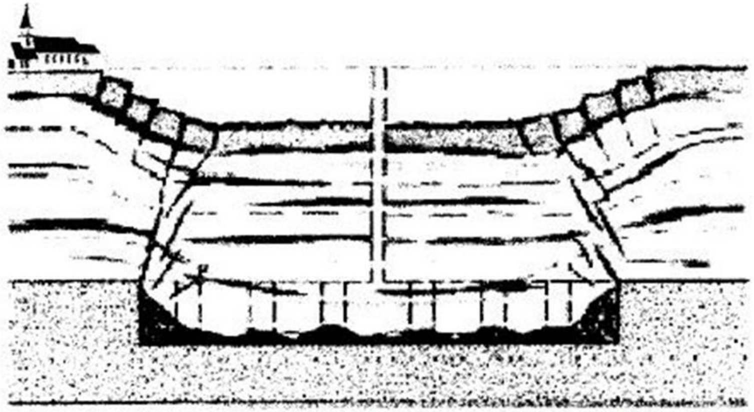
Civil Engineering

Heave in a tunnel excavated in sulphate bearing rock (Belchen tunnel)

Mining Engineering

Castellanza et al. (2005)

Effects of weathering of pillars in abandoned iron mines (Northern France)



Chemical mechanism: new material characterization

Long term stability of mineworkins and quarries (De Genaro, 2006):

Geotechnical data :

- pillar deformations
- roof and floor deformations
- pore water pressure

Environmental data :

- atmosphere temperature
- rock temperature
- hygrometry
- Water table level in the quarry
- atmosphere composition (CO_2, O)
- Variations of water table
- geochemical analysis of water

  (and solid phase)

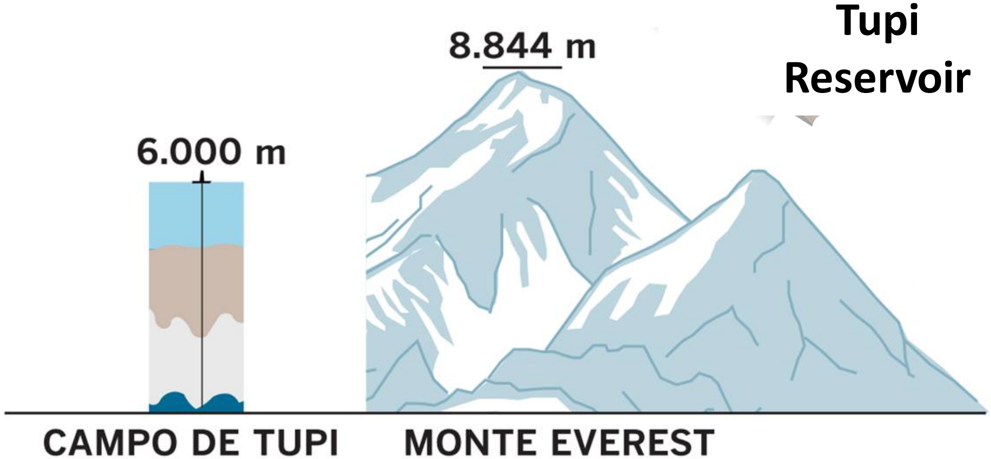
New Motivation:

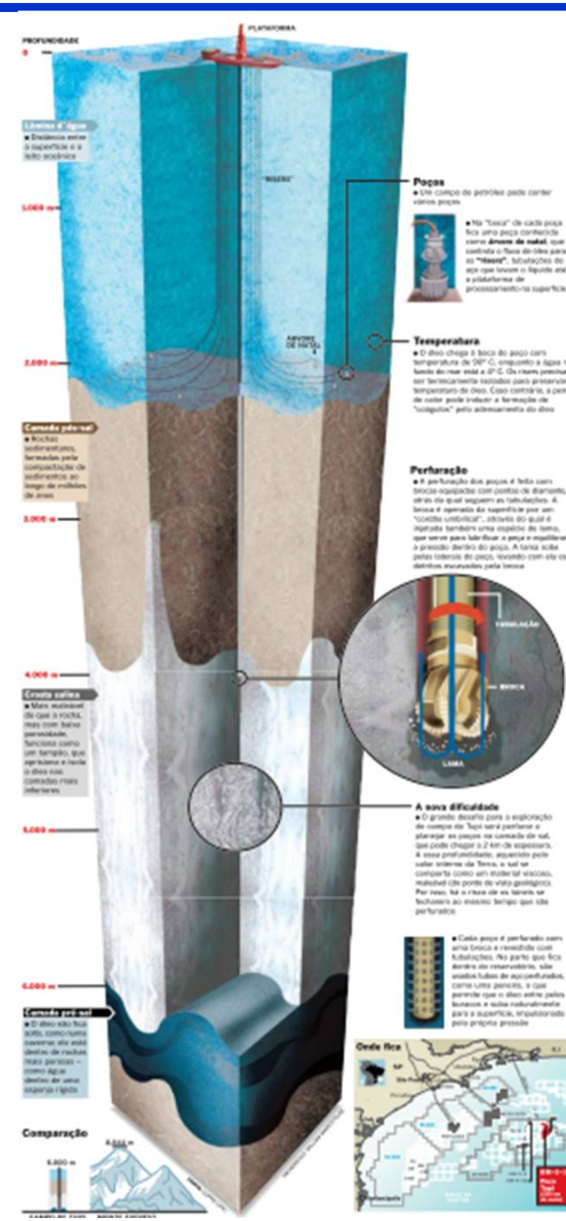
Carbonatic Oil Reservoirs

UFPE

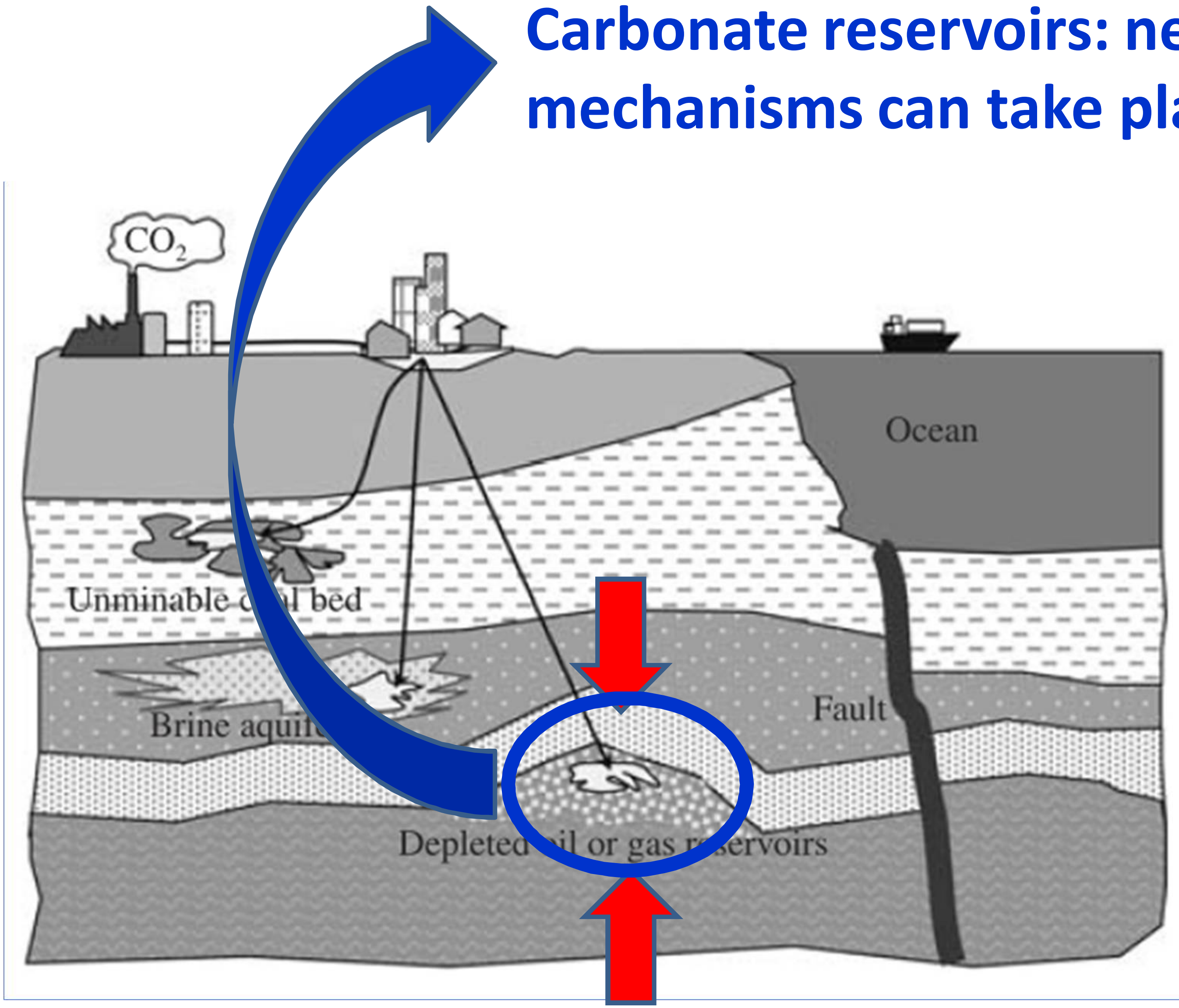
Brazilian Pre-Salt Reservoirs (ultra-deep waters reservoir):

- **Reservoir and cap rocks integrity (geomechanical and chemical)**
- **Reservoir properties (coupled HMC phenomena)**
- **CO2 injection (multiphase multispecies modeling)**





CO2 underground geological storage:



Carbonate reservoirs: new deformational mechanisms can take place in the medium

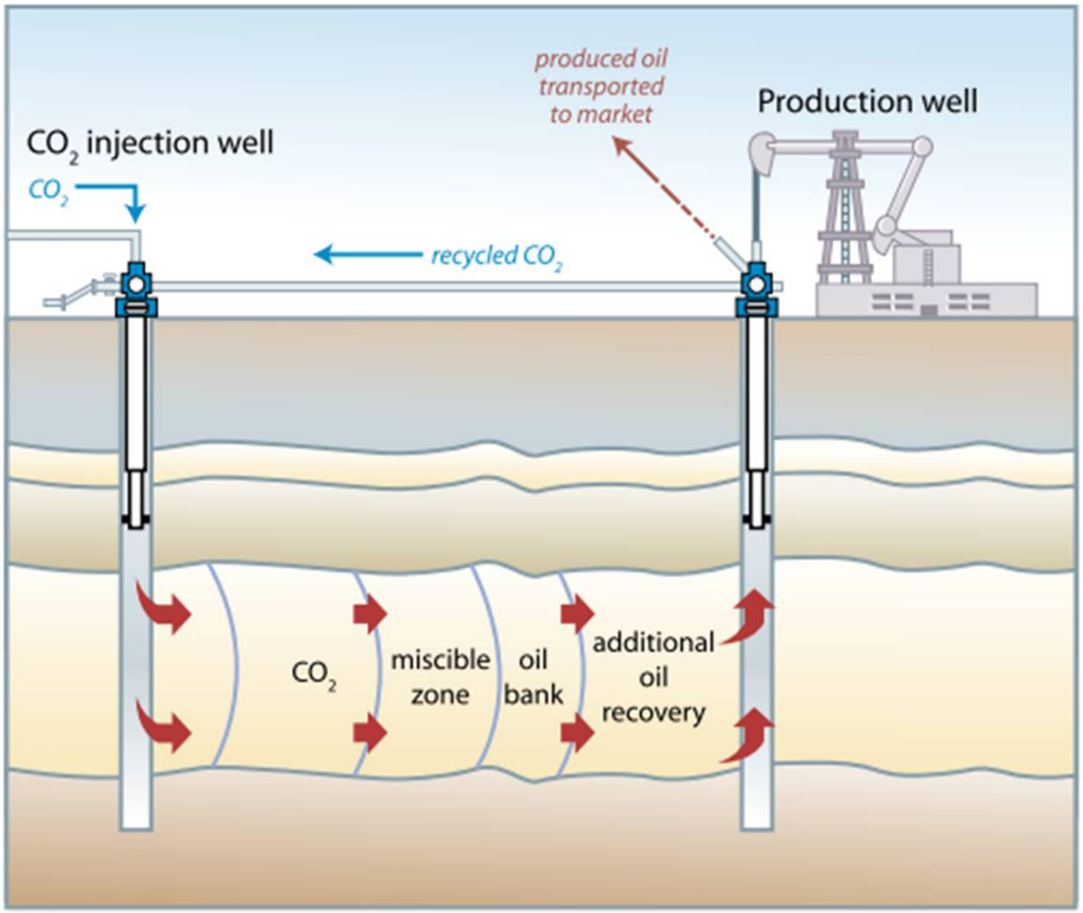
Rock-fluid chemical interactions

Waterweakening

[**Chemo-mechanical mechanism**]

CO2 underground geological storage:

Carbonate reservoirs: new deformational mechanisms can take place in the medium



$$CO_2 + H_2O = HCO_3^- + H^+$$

(water acidification)

$$CaCO_3(s) + H^+ = Ca^{2+} + HCO_3^-$$

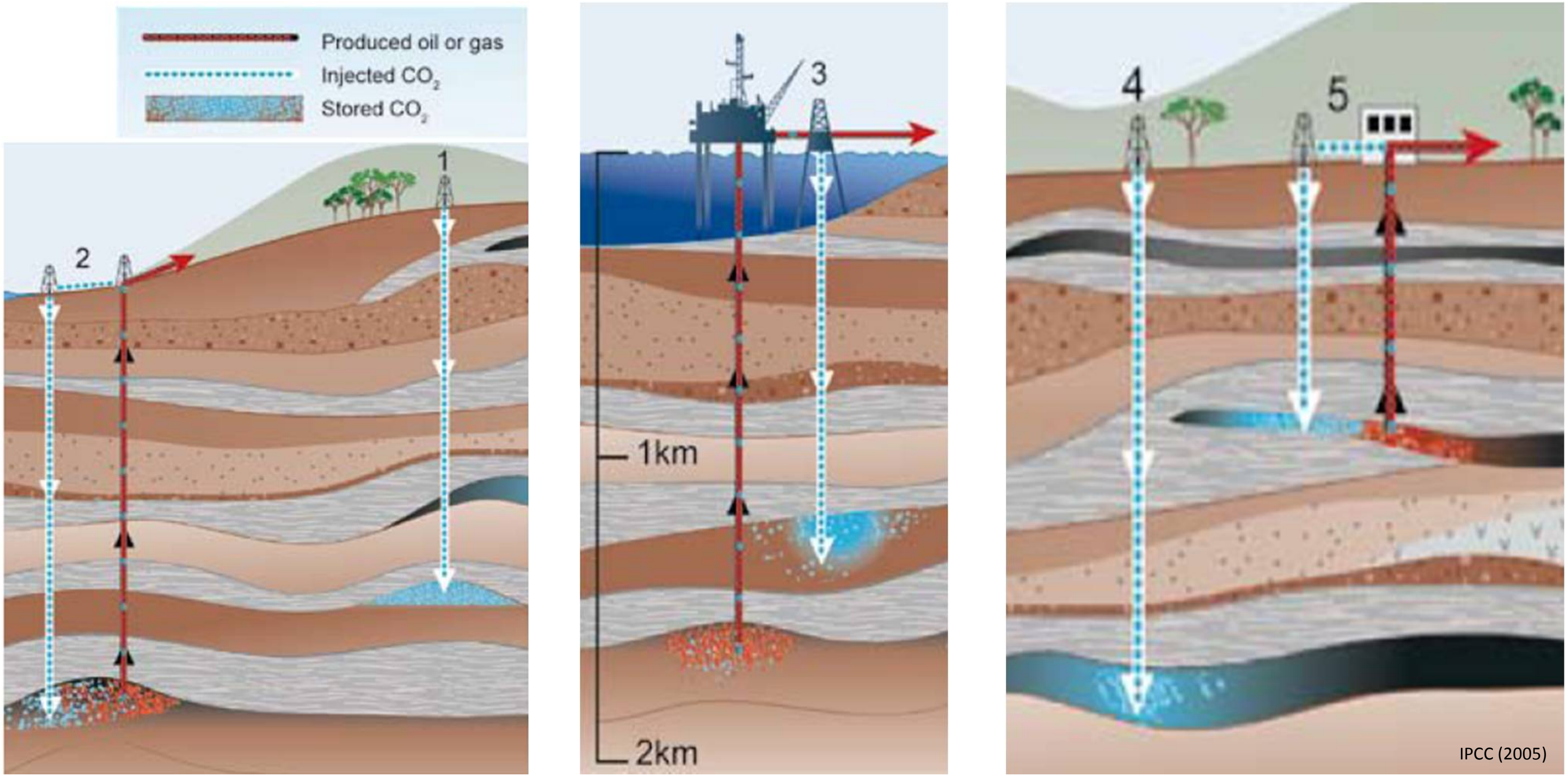
(calcite dissolution)

Waterweakening

[**Chemo-mechanical mechanism**]

CO2 Storage in Geological Formations

How can the geological CO_2 storage be done?



- **Oil fields**

1- Depleted reservoirs (gas/oil)
2- Enhanced oil recovery

- **Saline Aquifers;**

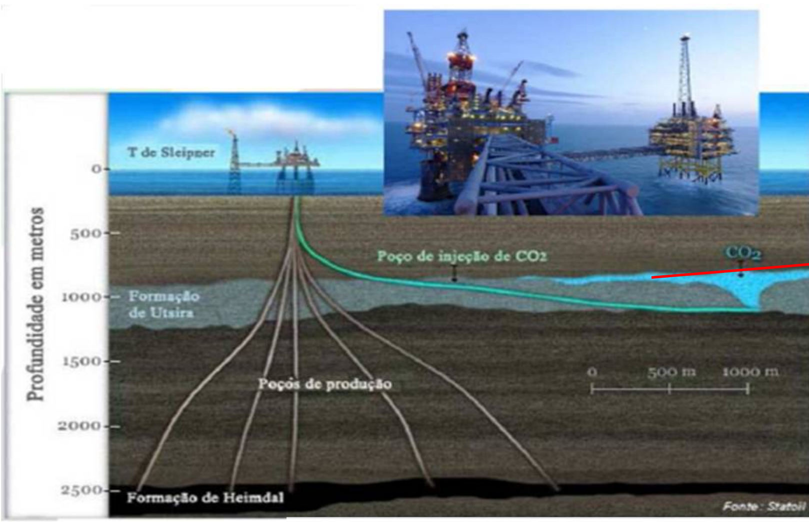
3- Deep unused saline water-saturated reservoir rocks.

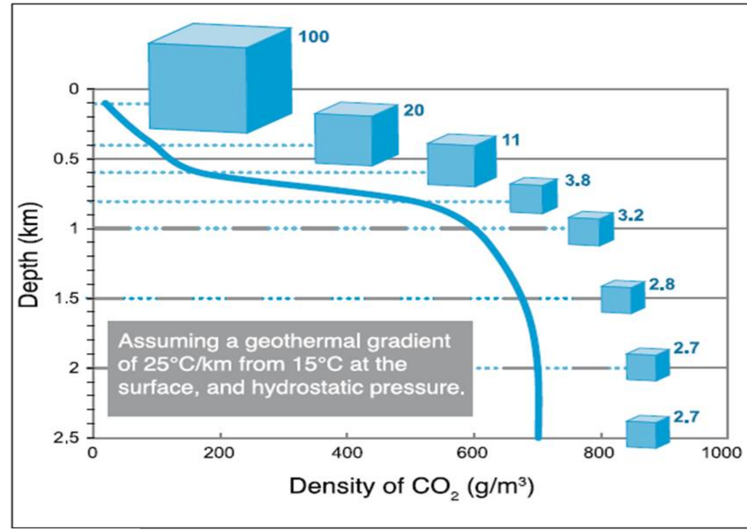
- **Coal layers.**

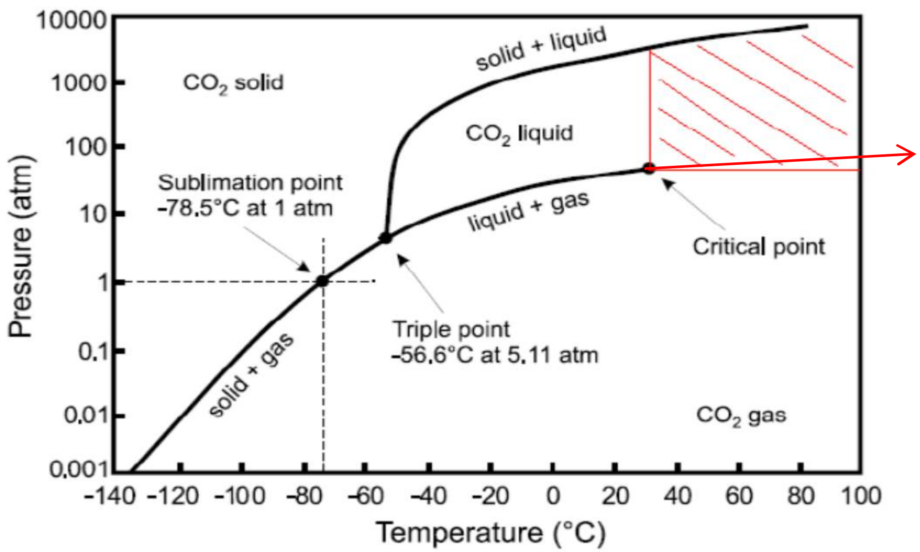
4- Deep Unmineable coal
5- ECBM Recovery

CO2 Storage in Geological Formations

How does CO2 behave when injected into geological formations?







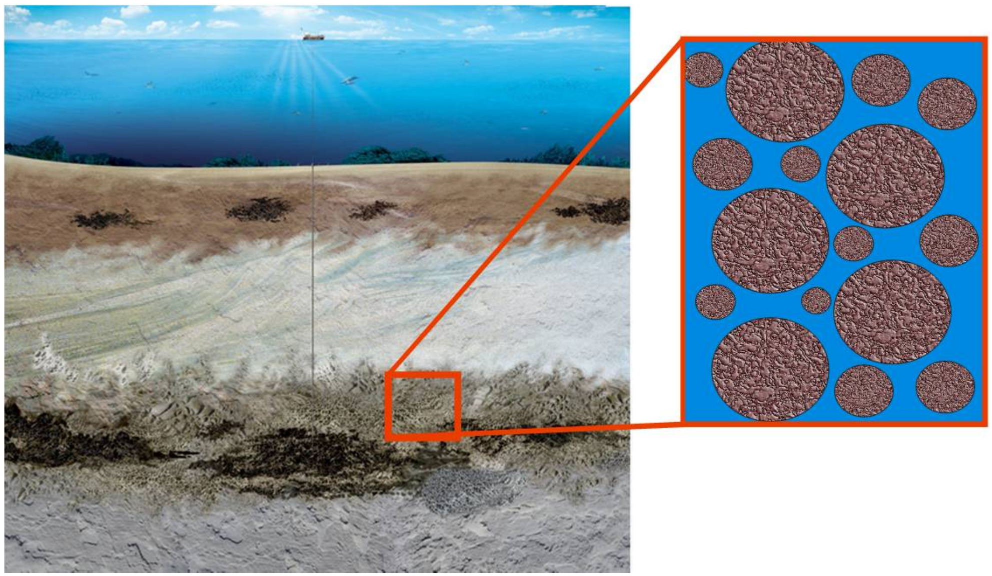
Supercritical CO_2

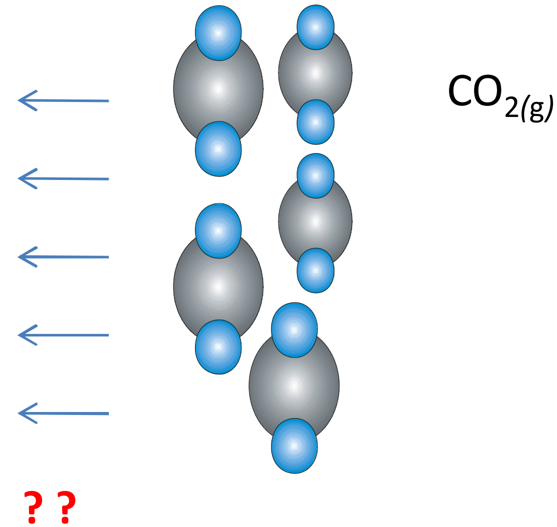
(gas as a liquid density)

More reactive: Exhibit the propensity to dissolve materials

CO2 Storage in Geological Formations

What can happen in porous media following CO2 injection?





Physical
Chemical

Main mechanisms to storage CO_2 into geological formations

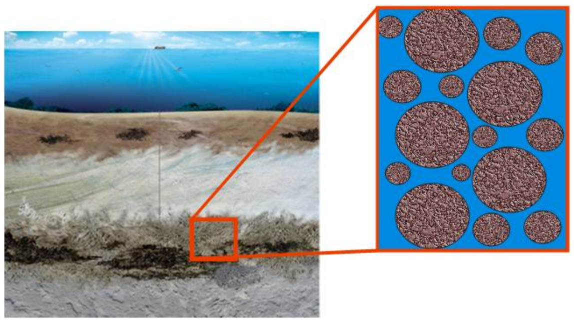
Fluid flow due to natural hydraulic gradientes and injection process;	Buoyancy caused by the density differences between CO2 and the formation fluid;	Diffusion, dispersion and fingering caused by constrast between CO2 injected and formation fluids;	**Dissolution into the formation fluid and porous media**	**Precipitation/ mineralization into the porous media**	Adsorption of CO2 onto organic material	Pore space trapping

Others

CO2 Storage in Geological Formations

What can happen in porous media following CO2 injection?

Dissolution of porous media

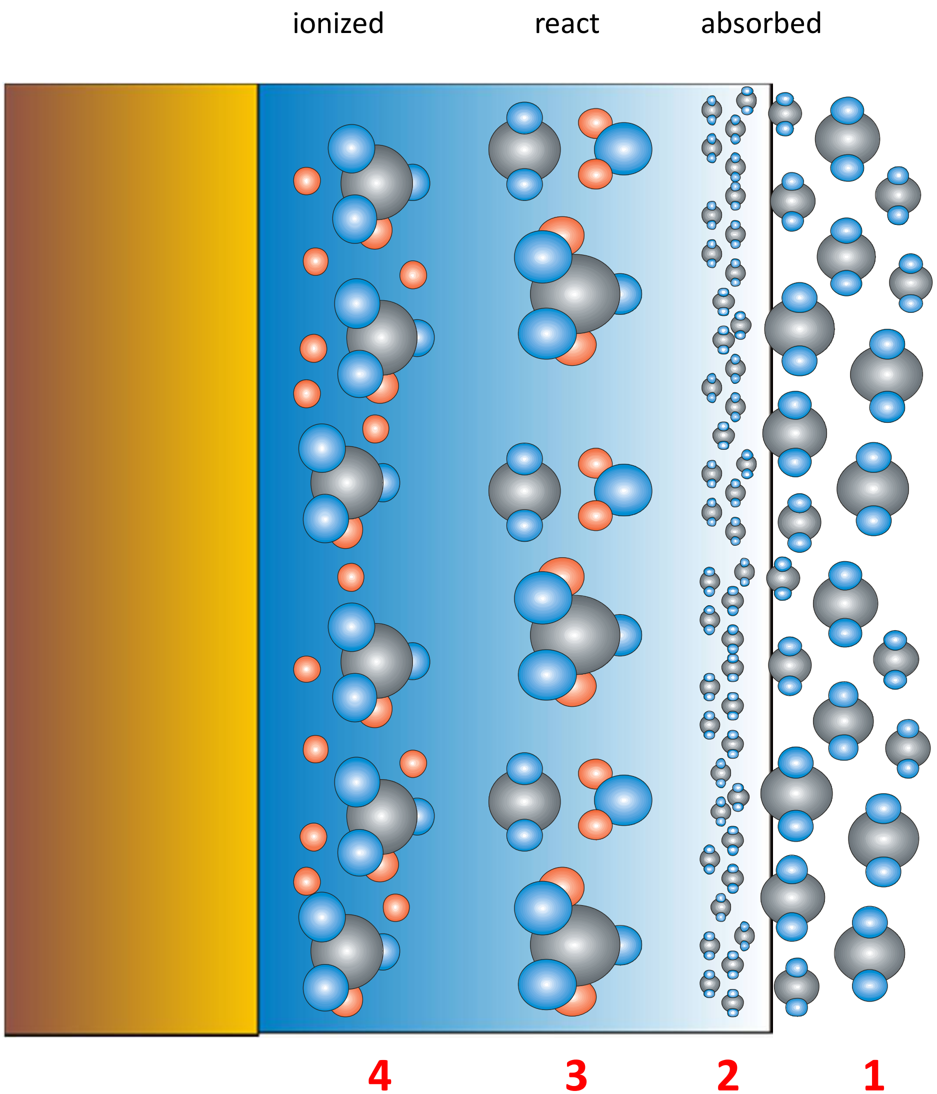


1. $CO_{2(g)}$

2. $CO_{2(aq)}$

3. $CO_{2(aq)} + H_2O_{(l)} \leftrightarrow H_2CO_{3(aq)}$

4. $H_2CO_{3(aq)} \leftrightarrow HCO_3^-{}_{(aq)} + H^+_{(aq)}$



CO2 Storage in Geological Formations

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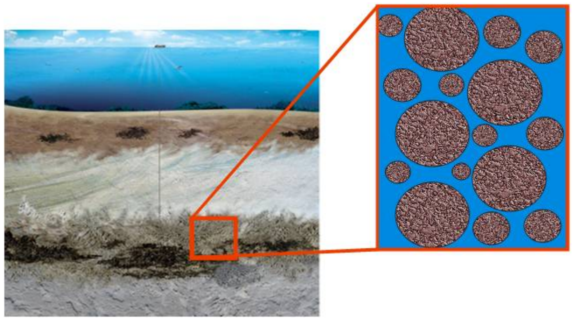

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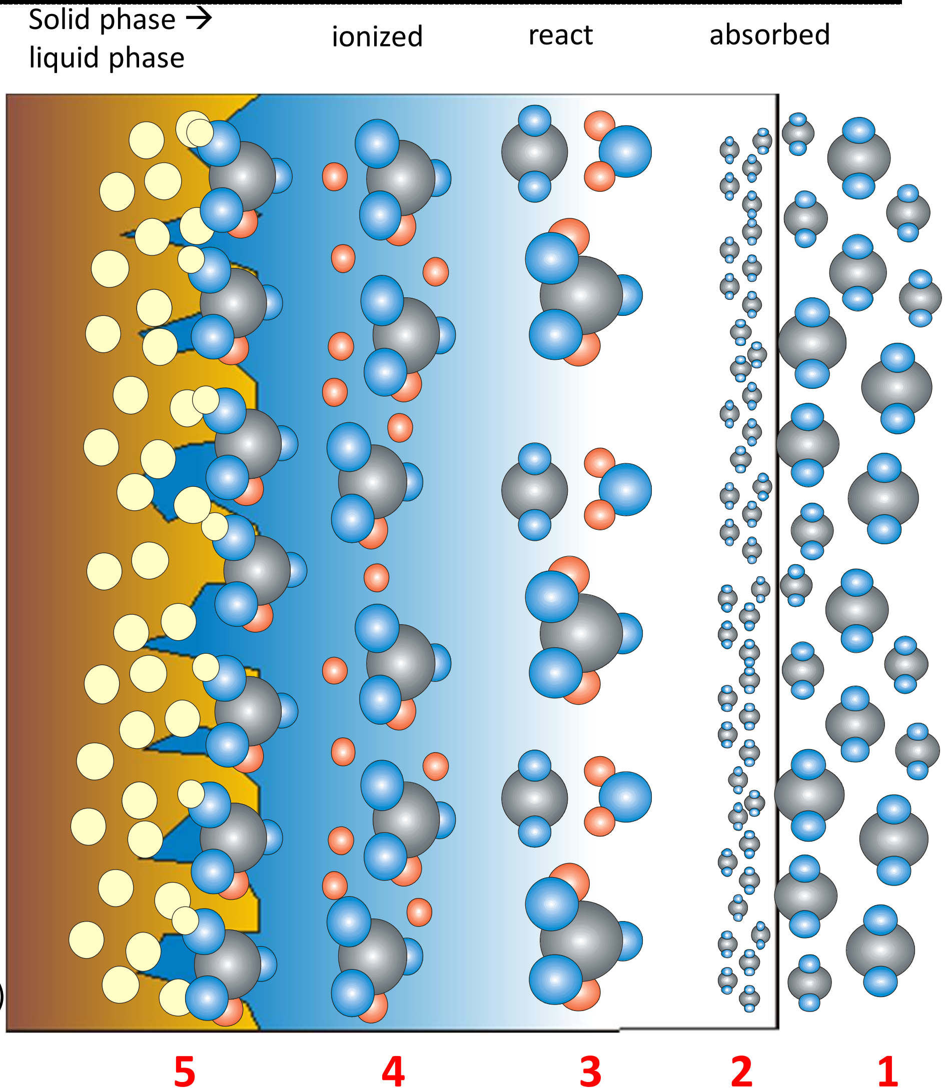
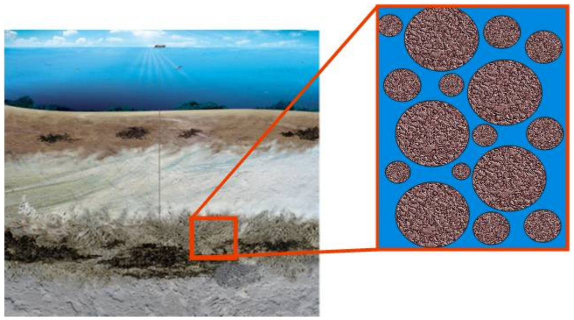
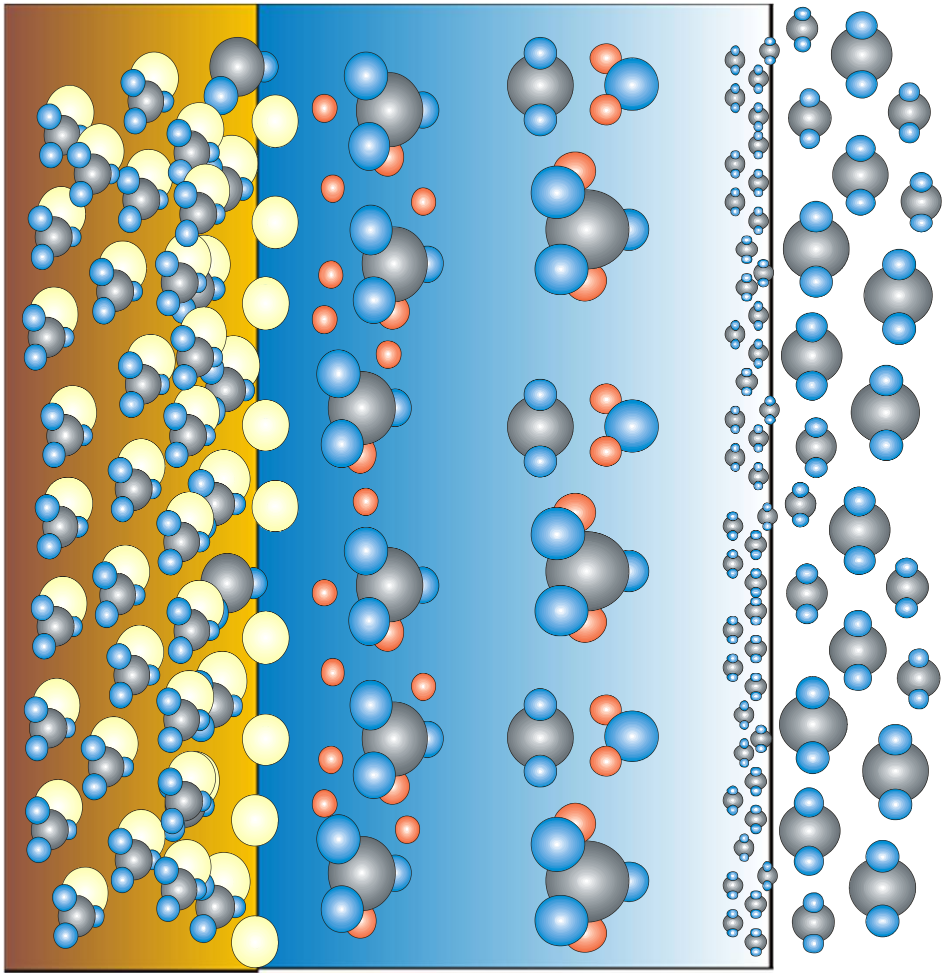


CO2 Storage in Geological Formations

What can happen in porous media following CO2 injection?

Precipitation and mineralization into the porous media





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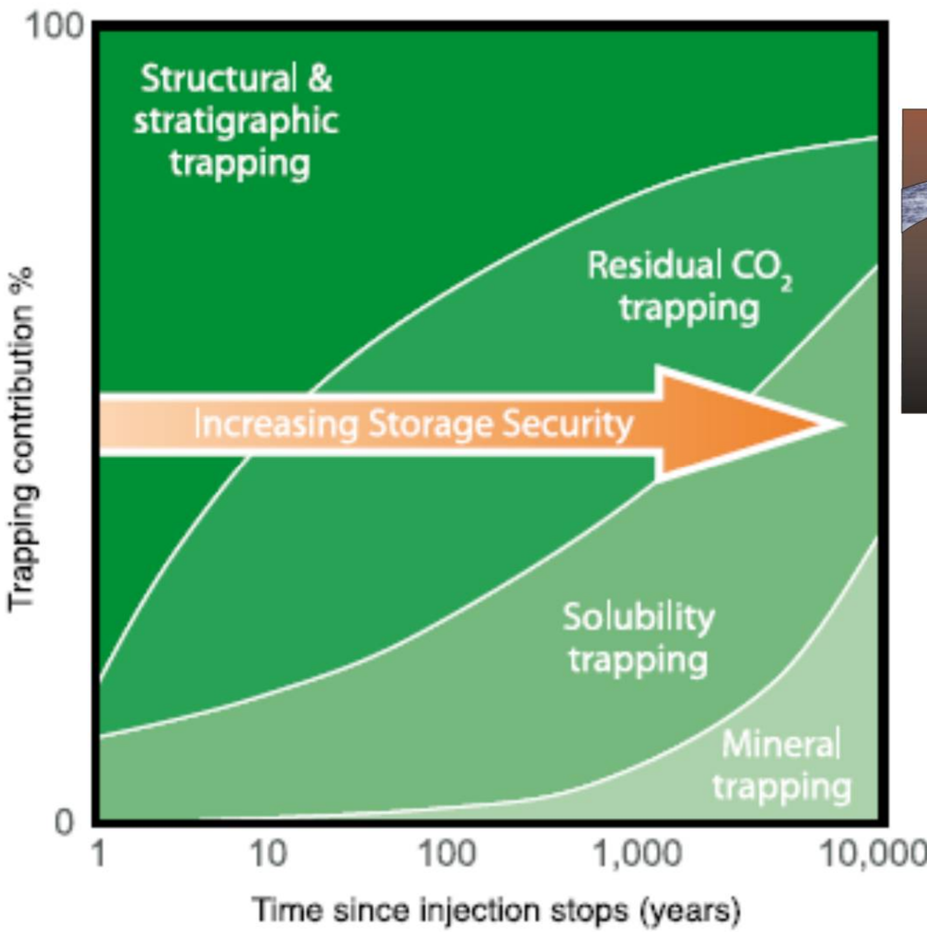
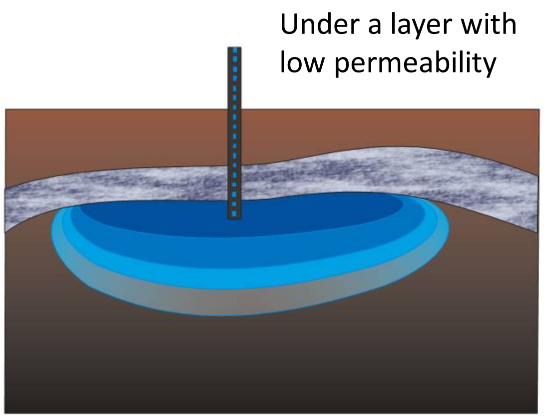
CO2 Storage in Geological Formations

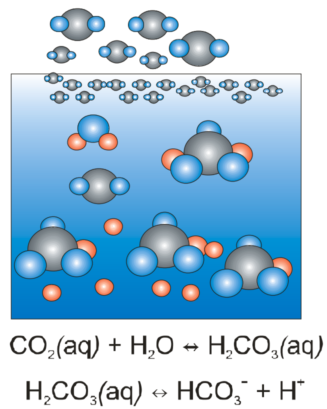
What can happen in porous media following CO2 injection?

[redacted]

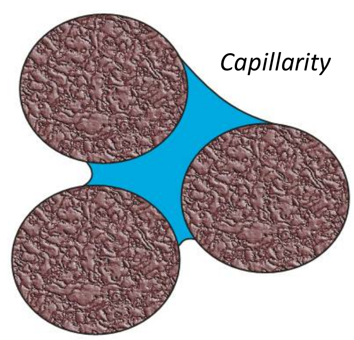




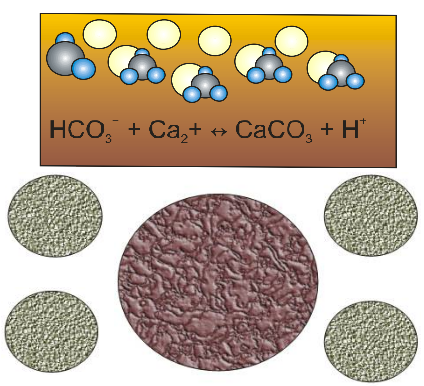
Structural & stratigraphic trapping



Solubility trapping



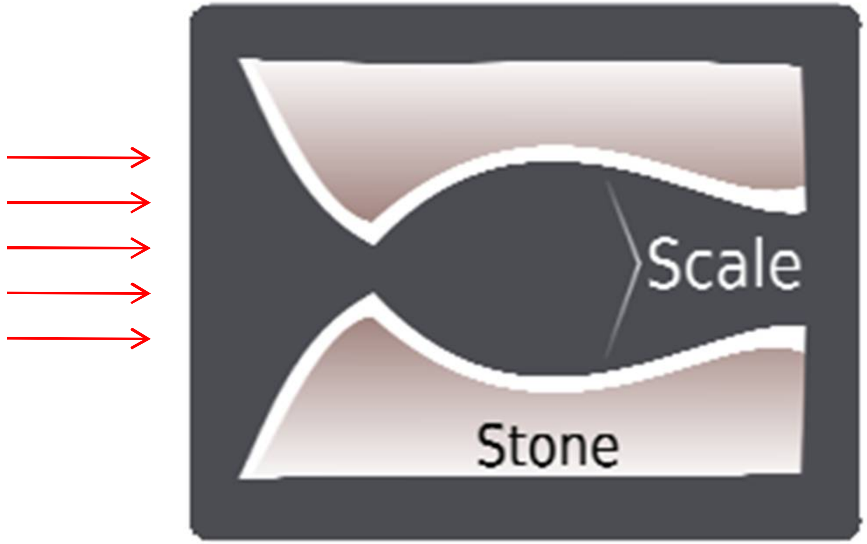
Residual CO2 trapping



Mineral trapping

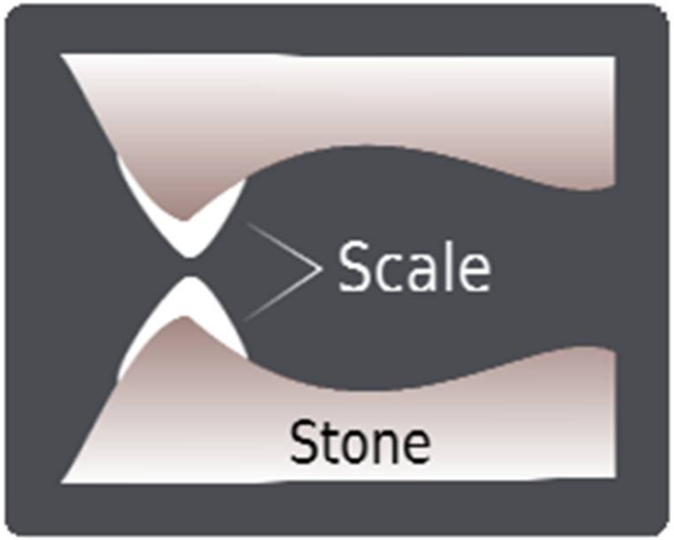
CO2 Storage in Geological Formations

Challenges: quantify changes of porosity and permeability due to precipitation.



Distributed precipitation

Changes in Porosity and Permeability



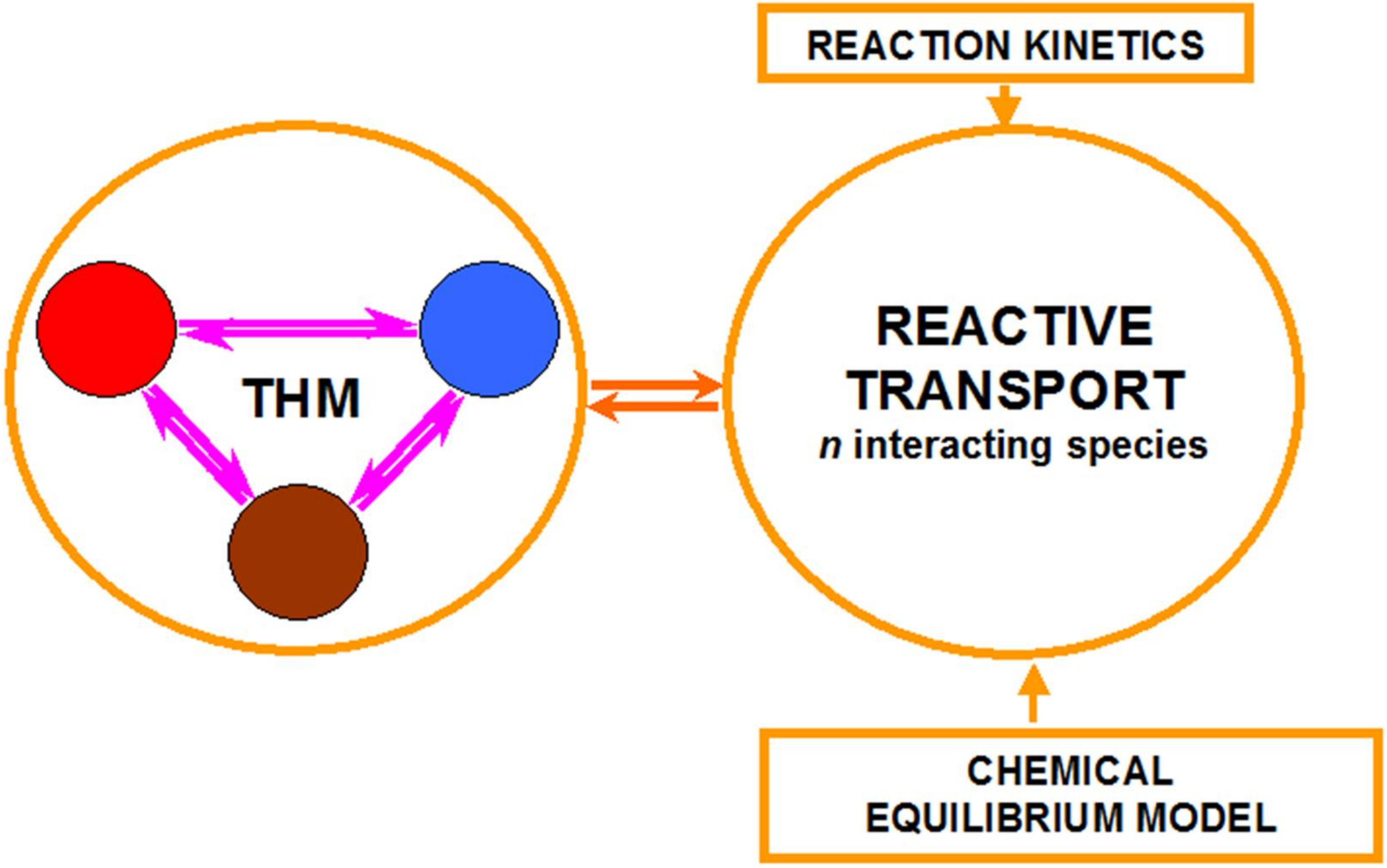
Precipitation located
Formation of disconnected porous

The permeability is greatly affected, not porosity.

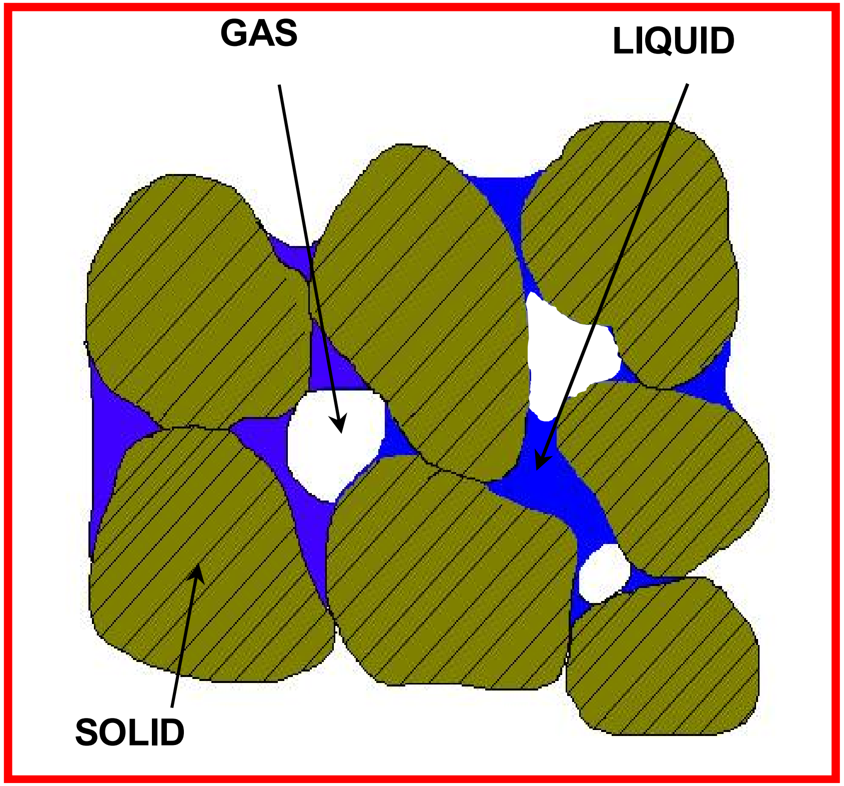
The only way to solve this problem is by perfoming experiments

Randhol & Larsen, 2010
(SINTEF Petroleum Research)
III International Seminar on Oilfield Water Management

Coupled THM and Reactive Transport Problem



Multiphase multispecies approach



The species are:

- mineral (-) : main mineral
- water (*w*) : as liquid or evaporated in the gas phase
- air (*a*) : dry air, as gas or dissolved in the liquid phase
- chemical species : interacting (reactive) species

The three phases are:

- gas (*g*) : mixture of dry air and water vapour
- liquid (*l*) : water + air dissolved + dissolved chemical species
- solid (*s*) : main mineral + absorbed cations + precipitated minerals

Reactive transport equations

$$\frac{\partial}{\partial t}(\phi S_w \rho_w c_i) + \nabla \cdot \mathbf{j}_i = R_i \quad (i = 1, \ldots, N)$$

Total Flow:

Chemical reactions

$$\mathbf{j}_i = \rho_w c_i \mathbf{q}_w + \mathbf{D}_w \nabla c_i + \phi S_w \rho_w c_i \dot{\mathbf{u}}$$

Advective

Non-advective (dispersion and diffusion)

Solid velocity

Reactive transport equations

$$\frac{\partial}{\partial t}(\phi S_w \rho_w c_i) + \nabla \cdot \mathbf{j}_i = R_i \quad (i = 1, \ldots, N)$$

- CHEMICAL INTERACTION OF *N* INTERACTING SPECIES
  - Slow reactions: kinetics controlled
  - Fast reactions: equilibrium controlled
- PHENOMENA CONSIDERED
  - Homogeneous reactions
    - Aqueous complex formation
    - Acid/base reactions
    - Oxidation/reduction reactions
  - Heterogeneous reactions
    - Cation exchange
    - Dissolution/precipitation of minerals (equilibrium and kinetics)
  - Other reactions
    - Radioactive decay
    - Linear sorption

Reactive transport equations

$$\frac{\partial}{\partial t}(\phi S_l \rho_l c_i) + \nabla \cdot \mathbf{j}_i = R_i \quad (i = 1,\ldots,N)$$

❑ CHEMICAL INTERACTION OF *N* INTERACTING SPECIES

❑ Slow reactions: kinetics controlled

- Rate of species production in kinetics-controlled reactions

$$r_m = A_m k_m \left| \Omega_p{}^r - 1 \right|^n$$

$$\Omega_p = \frac{Q_m}{K_m} \quad ; \quad Q_m = \prod_{j=1}^{N_c} a_j^{\nu_{mj}}$$

$$k_m = k_{25} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right]$$

❑ Fast reactions: equilibrium controlled

- A chemical equilibrium model is uses based on the minimization of Gibbs free energy

$$\underset{n_j^c, n_i^x}{minimize} \quad G = \sum_{j=1}^{N_c} \mu_j^c n_j^c + \sum_{i=1}^{N_x} \mu_i^x n_i^x$$

$$n_j^U = n_j^c + \sum_{i=1}^{N_x} \nu_{ij} n_i^x \quad (j = 1,\ldots,N_c)$$

$$n_i^x \geq 0 \quad (i = 1,\ldots, N_x)$$

$$n_j^c \geq 0 \quad (j = 1,\ldots, N_c)$$

  - Newton-Raphson algorithm
  - Lagrange multipliers to incorporate the restrictions of the system

NUMERICAL IMPLEMENTATION NEWTON-RAPHSON

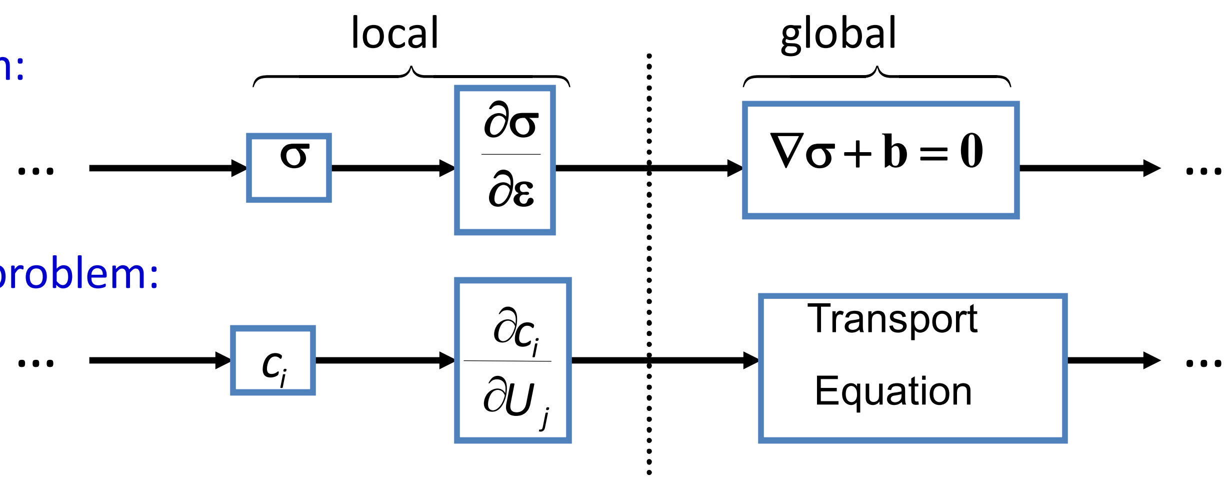
- Reactive Transport Equations

$$\frac{\partial}{\partial t}(\phi S_l \rho_l U_j) + \nabla \cdot \left(\rho_l Ua_j \mathbf{q}_l + \mathbf{D}_l \nabla Ua_j + \phi S_l \rho_l U_j \dot{\mathbf{u}} \right) + R_j^{irrev} = 0 \quad (j = 1, \ldots, N_c)$$

- Analogy with the mechanical problem

Mechanical problem:

Reactive transport problem:



- Tangent matrix

$$\left(\frac{\partial Ua_j}{\partial U_k}, \frac{\partial X}{\partial U_k} \right)$$

HM-C Couplings

Mechanical problem for geomaterials:

- Equilibrium Equation:

$$\nabla \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$$

- Principle of Effective Stresses:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \boxed{p_f \cdot \mathbf{I}}$$

New mechanisms!!!

- Stress-strain relationship:

$$\boxed{d\boldsymbol{\sigma}'} = \mathbf{D} \cdot d\boldsymbol{\varepsilon} + \mathrm{L} \cdot dP_c + \mathrm{H} \cdot dX_d$$

Specific for each geomaterial

HM-C Couplings

HYDRO-MECHANICAL COUPLINGS:

- Rock porosity:

$$\frac{\partial}{\partial t}\left[(1-\phi)\rho_s\right]+\nabla\left[(1-\phi)\rho_s.\dot{\mathbf{u}}\right]=0$$

(mass conservation of solids)

(material derivative)

$$\frac{d\,\bullet}{dt}=\frac{\partial\,\bullet}{\partial t}+\dot{\mathbf{u}}\cdot\nabla\,\bullet$$

$$\frac{d\phi}{dt}=\frac{(1-\phi)}{\rho_s}\frac{d\rho_s}{dt}+(1-\phi)\frac{d\varepsilon_v}{dt}$$

(changes of porosity as

a function of volumetric strains)

- Rock permeability:

$$\mathbf{k}=\mathbf{k_i}\,\exp\left[b(\phi-\phi_i)\right]$$

HM-C Couplings

HYDRO-MECHANICAL COUPLINGS:

Chemical coupling:
Porosity will change also due to mineral dissolution/precipitation!!!!!
(new term in mass conservation equation)

- **Rock porosity:**

$$\frac{\partial}{\partial t}\left[(1-\phi)\rho_s\right]+\nabla\left[(1-\phi)\rho_s\,\dot{\mathbf{u}}\right]=\mathbf{f}$$

(mass conservation of solids)

(material derivative)

$$\frac{d\,\bullet}{dt}=\frac{\partial\,\bullet}{\partial t}+\dot{\mathbf{u}}\cdot\nabla\,\bullet$$

$$\frac{d\phi}{dt}=\frac{(1-\phi)}{\rho_s}\frac{d\rho_s}{dt}+(1-\phi)\frac{d\varepsilon_v}{dt}$$

+ dissolution/precipitation term

- **Rock permeability:**

$$\mathbf{k}=\mathbf{k_i}\,\exp\left[b(\phi-\phi_i)\right]$$

HM-C Couplings

Changes of porosity due to mineral dissolution/precipitation:

$$\frac{D\phi}{Dt} = \frac{(1-\phi)}{\rho_s}\frac{D\rho_s}{Dt} + (1-\phi)\nabla\cdot\dot{\mathbf{u}} - \frac{Dv_T}{Dt}$$

chemical changes of porosity

$$v_T = \text{total mineral volume} = \sum_m \bar{v}_m c_m$$

$\bar{v}_m$: molar volume (m^3/mol) of mineral m

c_m : concentration (mol/m^3 of rock) of mineral m

Intrinsic permeability changes:

$$\mathbf{k}(\phi) = \mathbf{k}(\text{mechanical, thermical and chemical problems})$$

Numerical implementation (Compiler: Intel Fortran; IDE: CodeBlocks; OS: Linux)

Numerical approach

- Finite elements in space
- Finite differences in time
- Implicit time integration
- Simultaneous solution of the mechanical, hydraulic, thermal and reactive transport equations
- Full Newton-Raphson for iterative procedure to solve the set of nonlinear equations
- Solver (non-symmetric matrix)
  - LU decomposition and backsubstitution
  - Conjugate Gradient Squared Method with block diagonal preconditioning
  - PARDISO (MKL)
- Convergence tolerances in terms of variable corrections *and* residuals
- Coupled to a reactive transport module

Main features

- Coupled thermo-hydro-mechanical-chemical (THMC) analyses in 1, 2 and 3 dimensions
- Partial analyses are possible
- General treatment of transport processes
- Specific consideration of unsaturated porous media under non-isothermal conditions:
  - Constitutive laws (thermal, hydraulic, mechanical)
  - Equilibrium restrictions (vapour pressure, air dissolution)
  - Chemical equilibrium and kinetics for chemical species interaction
- Thermo-hydro-mechanical joint element
- Sequential and parallel versions
- Staggered fully-coupled scheme THM – C

Numerical implementation
(Compiler: Intel Fortran; IDE: CodeBlocks; OS: Linux)

UFPE

■ Numerical approach

- ❑ Fi
- ❑ Fi
- ❑ In
- ❑ Si hy ec
- ❑ Fu pr ec
- ❑ S
- ❑ Cc cc
- ❑ Coupled to a reactive transport module

■ Main features

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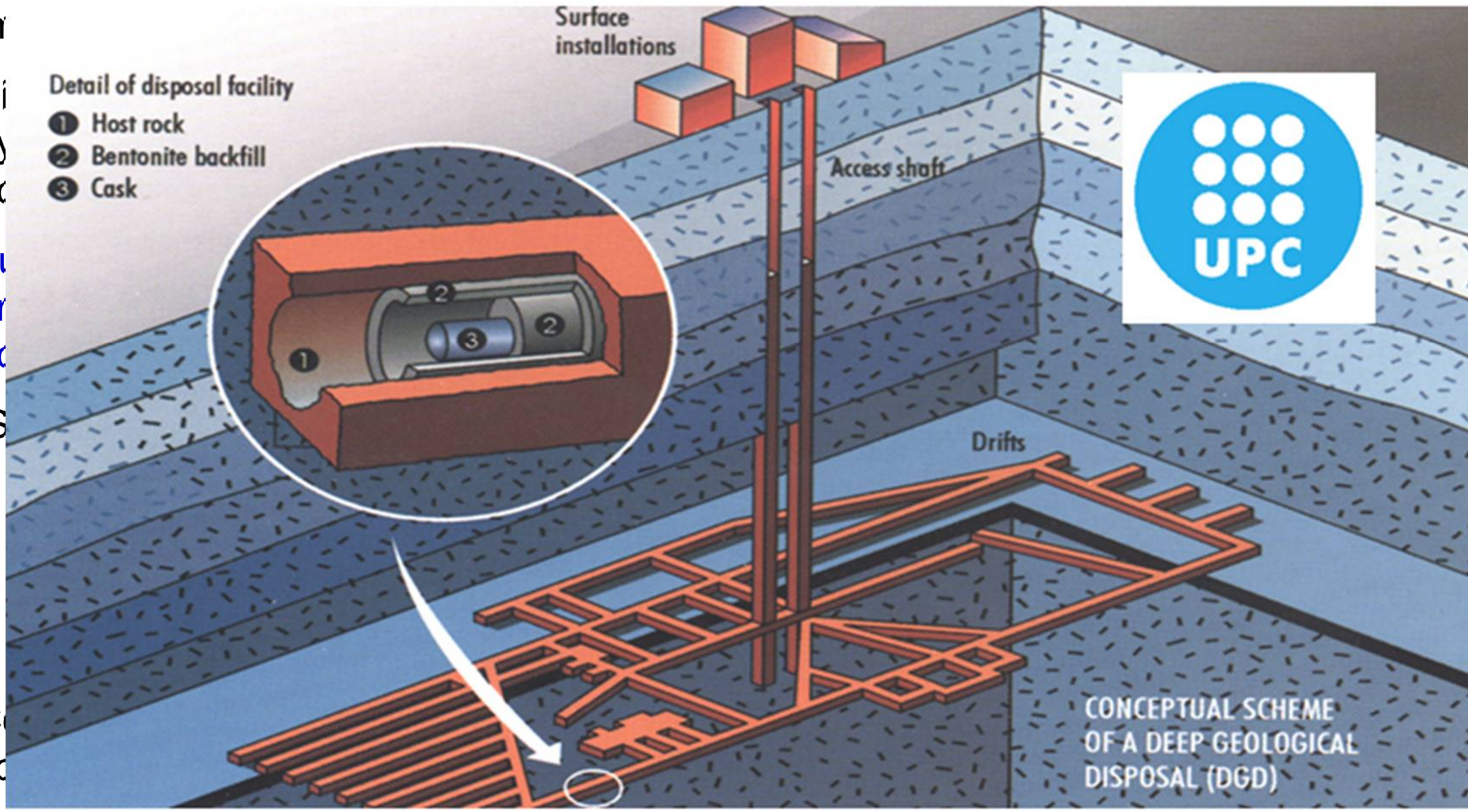
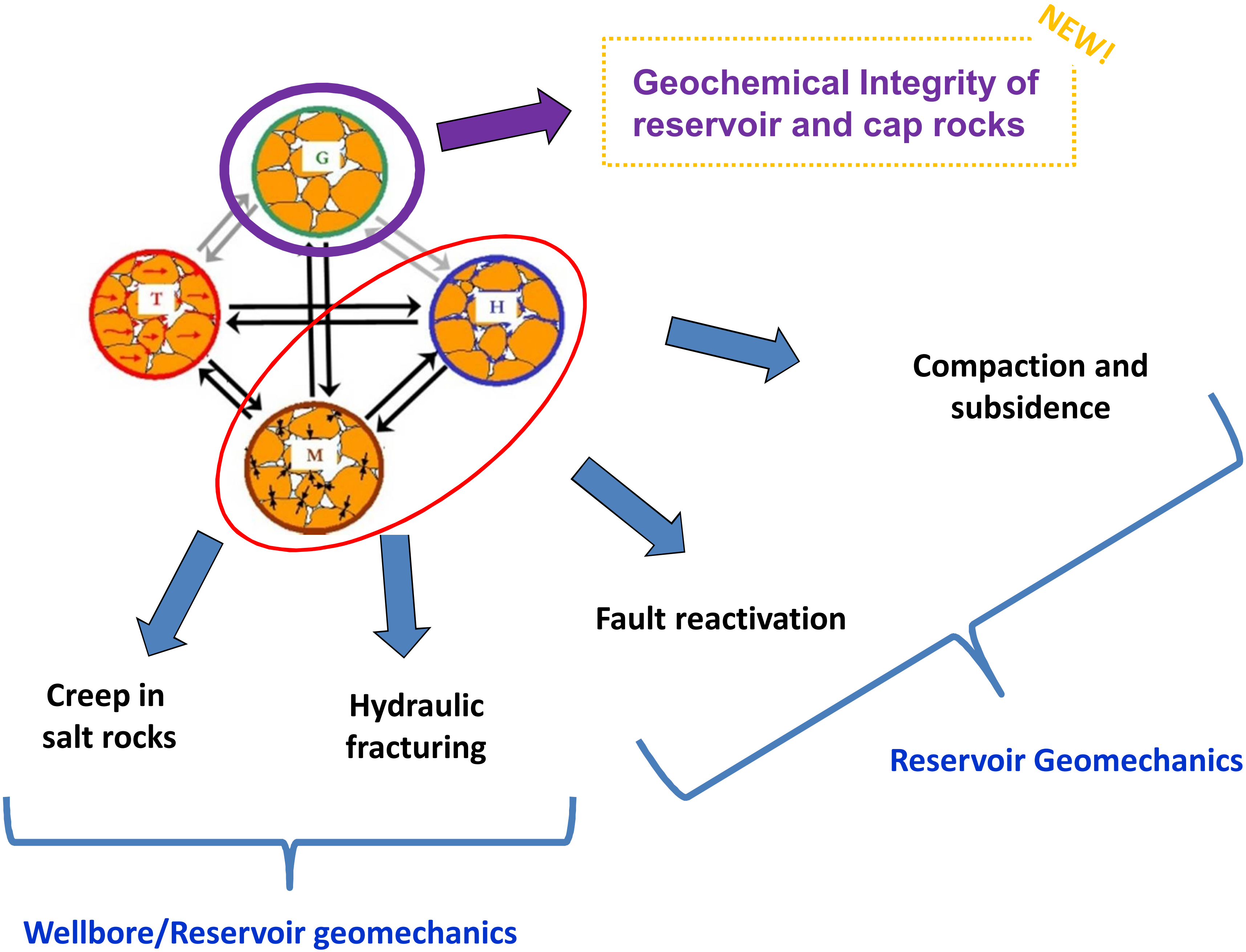
THM – C

Deep geological disposal

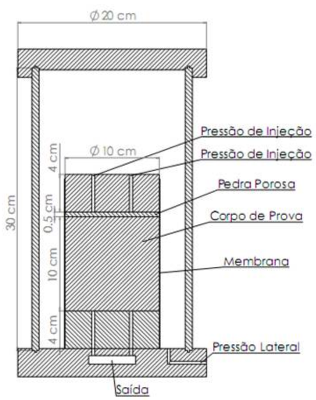



NEW!
Geochemical Integrity of reservoir and cap rocks
G
T
H
M
Compaction and subsidence
Fault reactivation
Creep in salt rocks
Hydraulic fracturing
Reservoir Geomechanics
Wellbore/Reservoir geomechanics

RESEARCH LINES – LABORATORY TESTS

Integrity of Carbonate Rocks Subjected to Mechanical and Chemical Actions

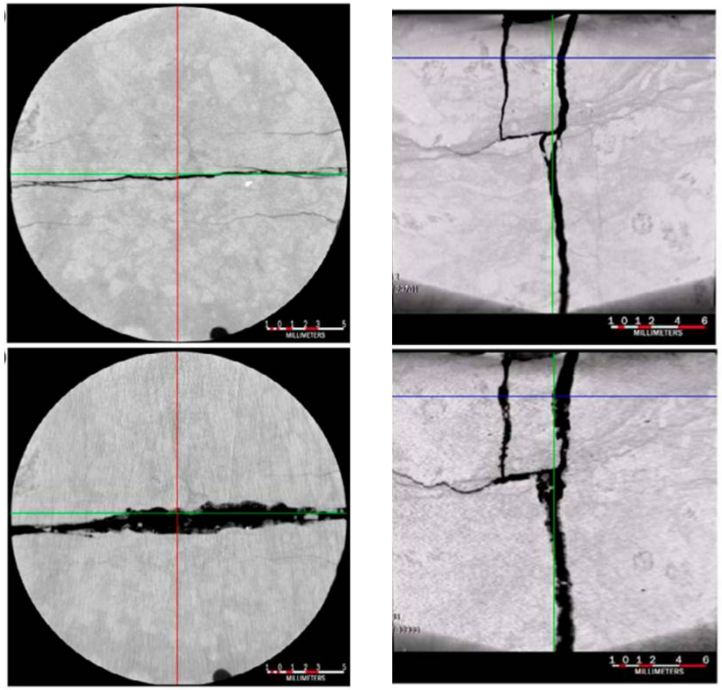
Matrix:



before

after

Fracture:



B.R. Ellis et al. / Energy Procedia 4 (2011) 5327–5334

RESEARCH LINES – LABORATORY TESTS

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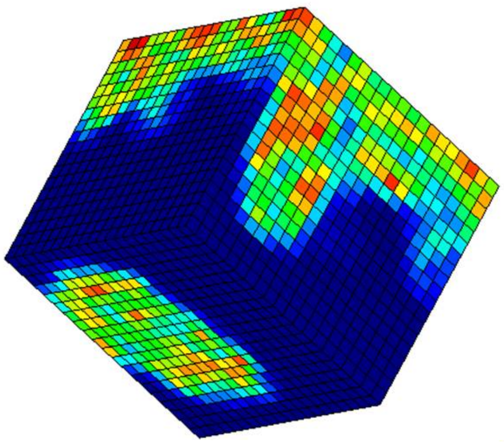
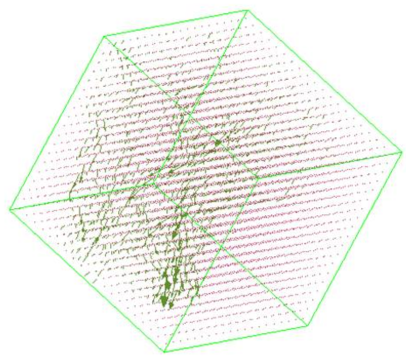
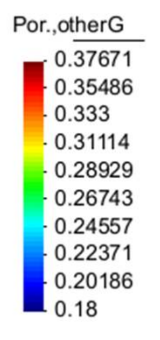
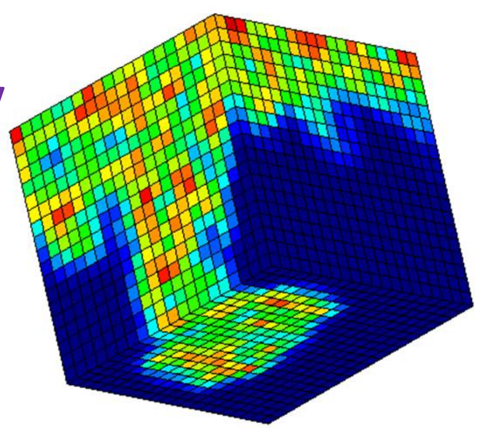




Porosity





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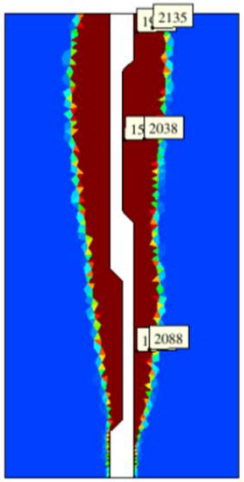
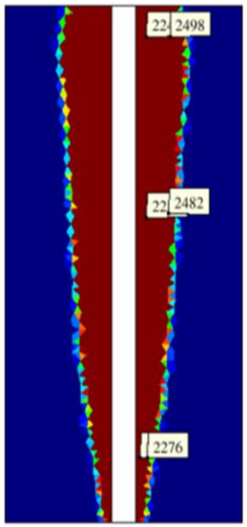
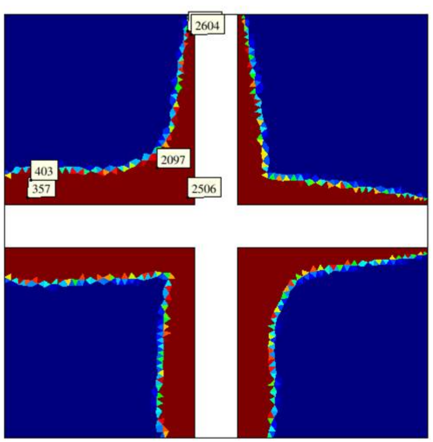
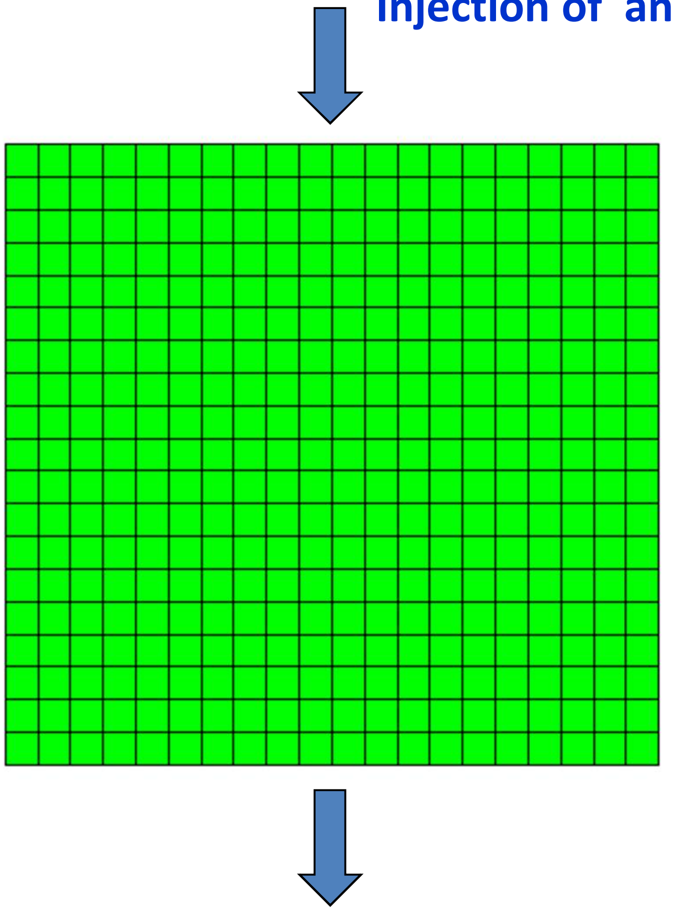






2D and 3D MODEL

Injection of an under-saturated water



Pressure at the top: $P + \Delta P$; ΔP =0.1MPa

Dissolution front of mineral

Pressure at the bottom: P

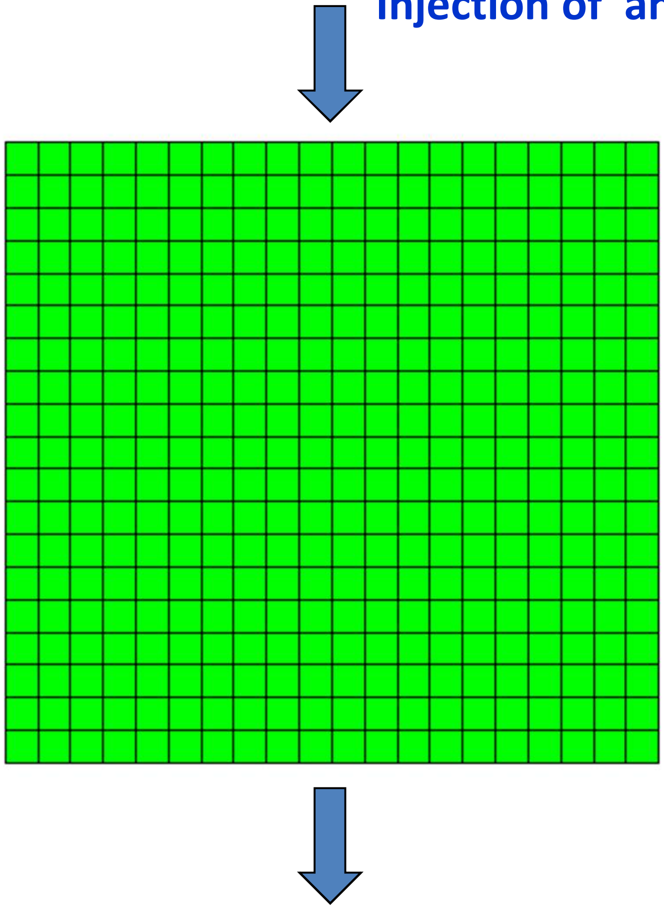
Initially:

- porosity and permeability: constants

- mineral: randomically distributed

2D and 3D MODEL

Injection of an under-saturated water



Pressure at the top: *P* + Δ*P* ; Δ*P* =0.1MPa

$$\frac{D\phi}{Dt} = \frac{(1-\phi)}{\rho_s}\frac{D\rho_s}{Dt} + (1-\phi)\nabla\cdot\dot{\mathbf{u}} - \frac{Dv_T}{Dt}$$

$$\mathbf{K} = \mathbf{K}_0 e^{b(\phi-\phi_0)}$$

$$\mathbf{K}_0 = 10^{-18}\mathbf{I} \quad (\mathrm{m}^2)$$

$$\mathrm{b} = 75$$

Tendency to develop preferencial paths (channels for fluid flow)

Pressure at the bottom: *P*

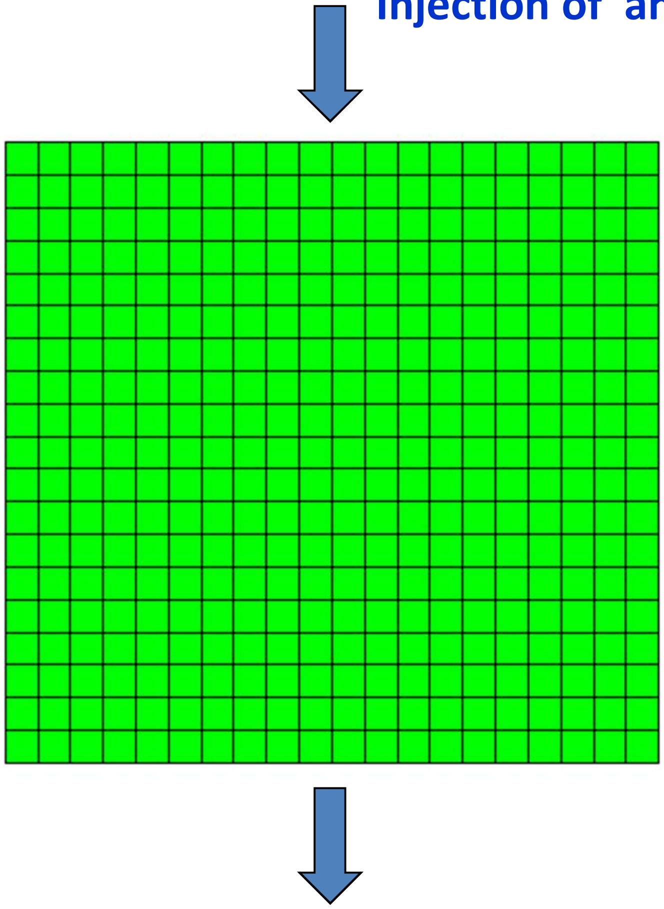
Initially:

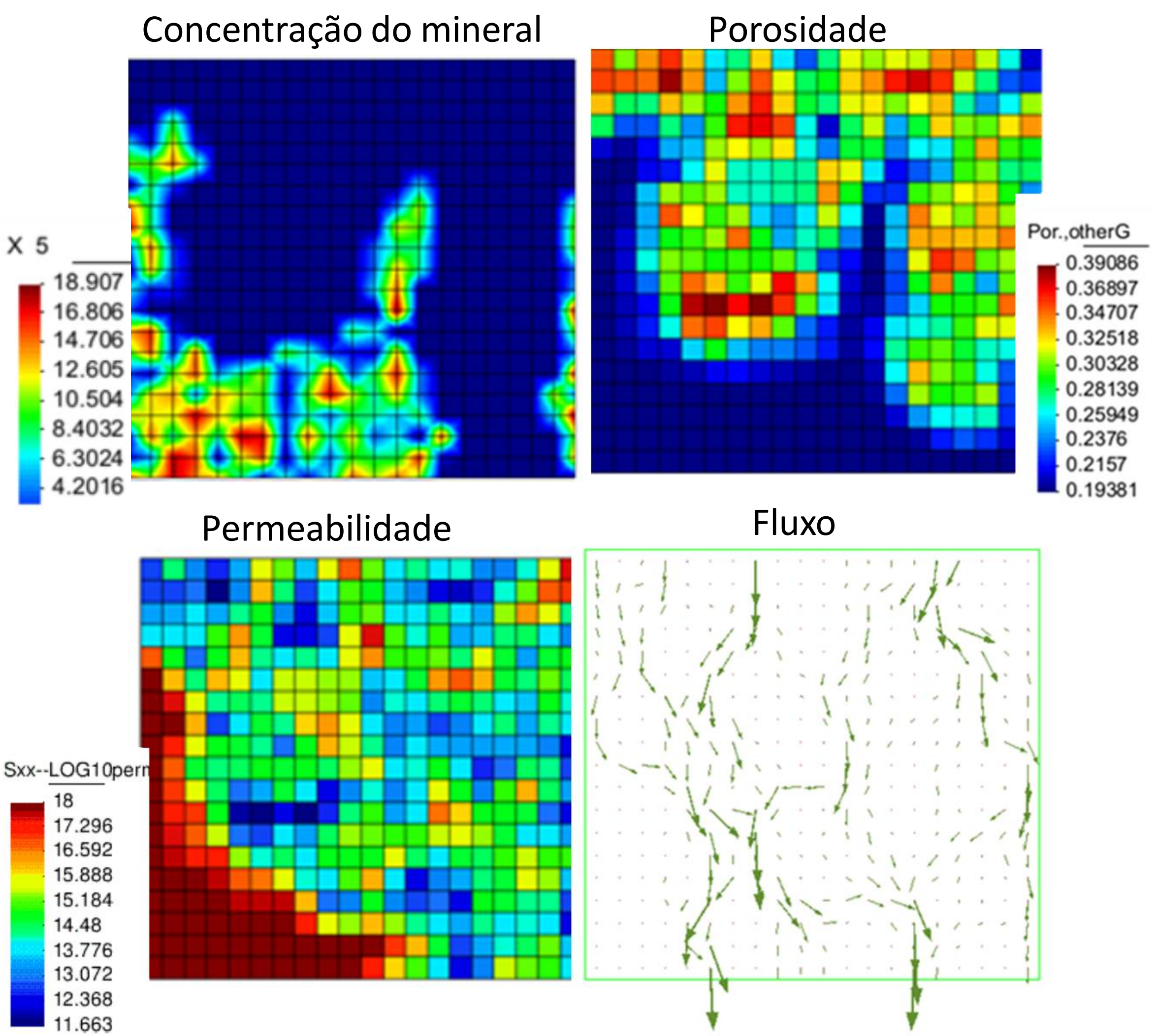
- porosity and permeability: constants

- mineral: randomically distributed

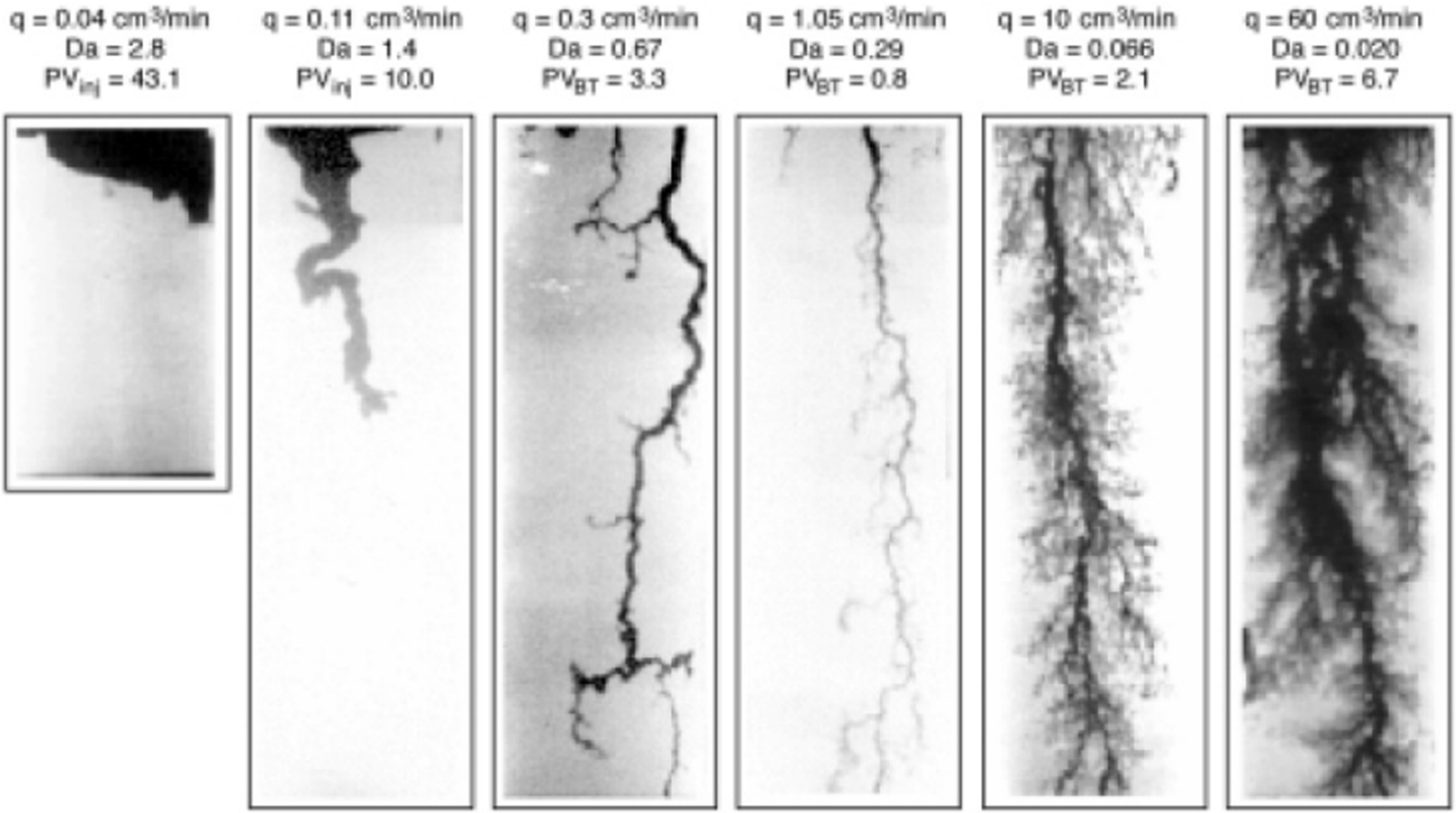
2D MODEL

Injection of an under-saturated water



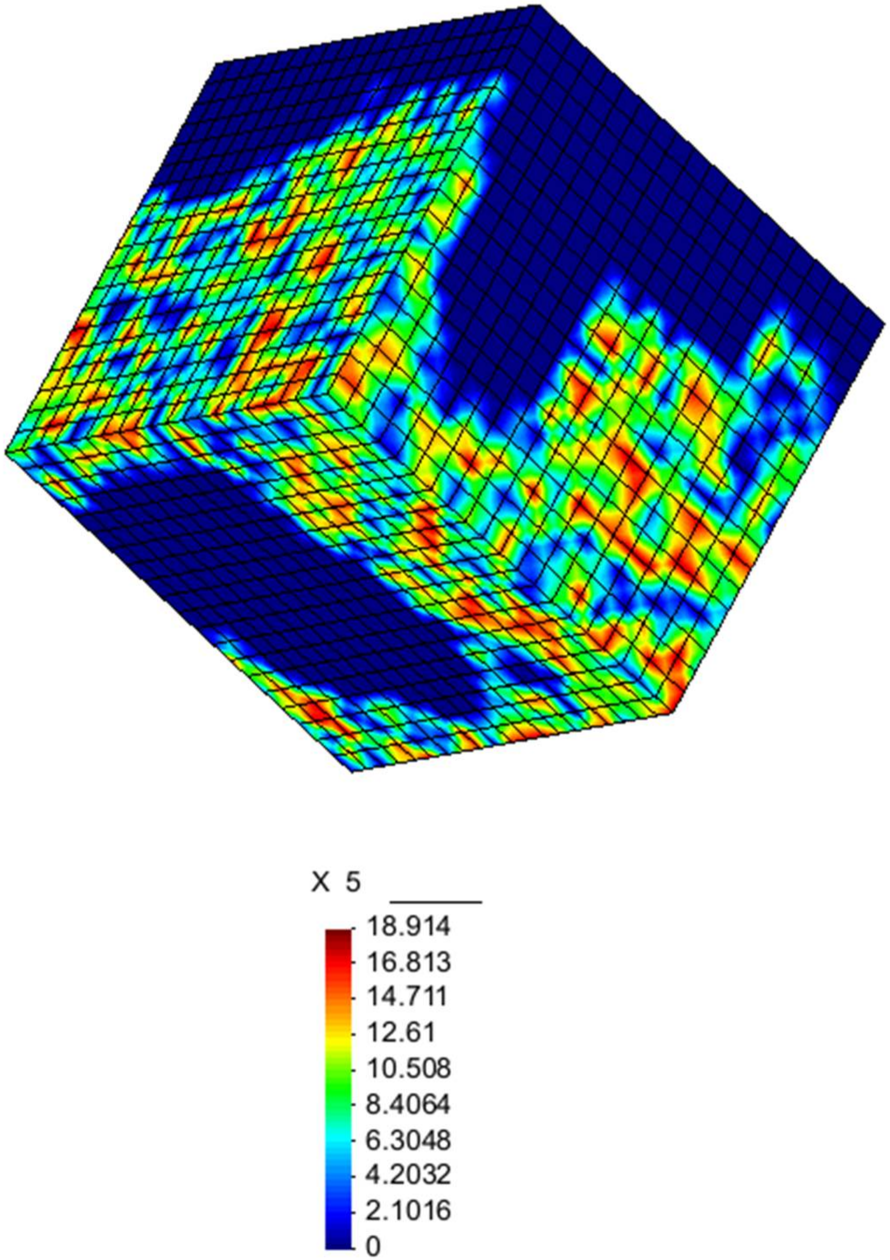


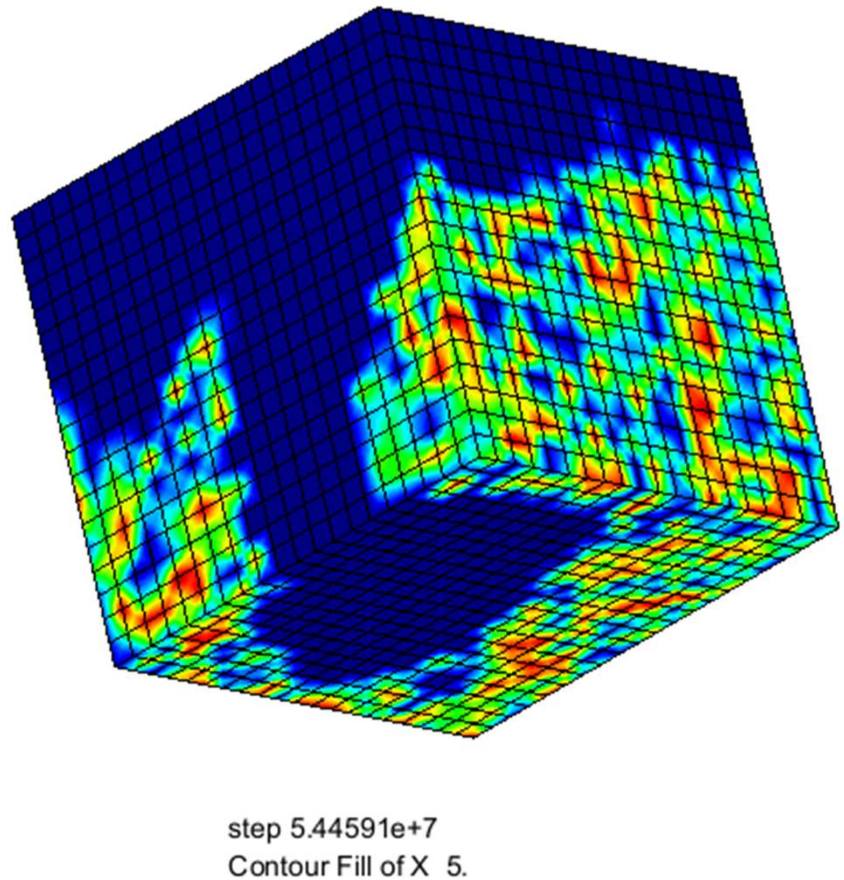
2D and 3D MODEL

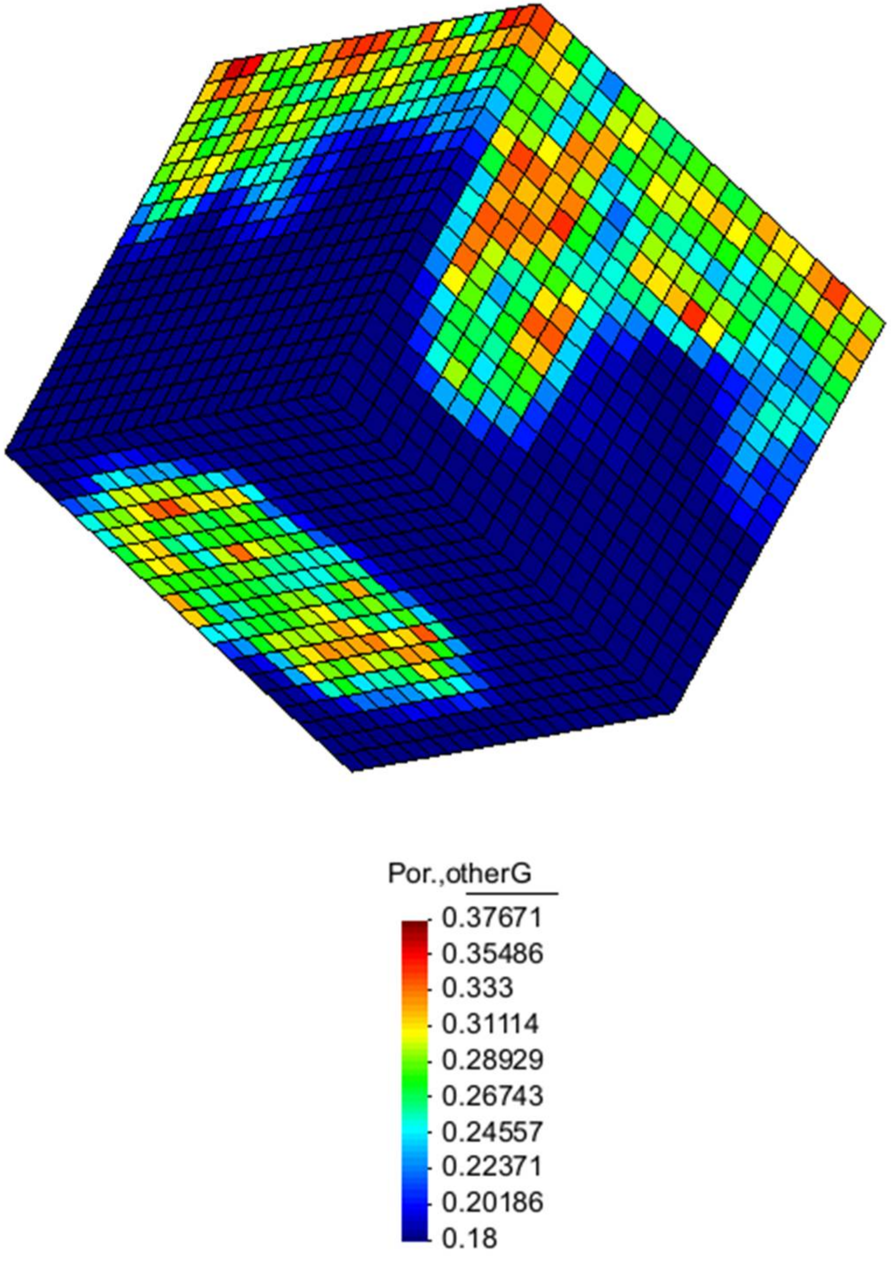


(Pereira & Fernandes, 2009)

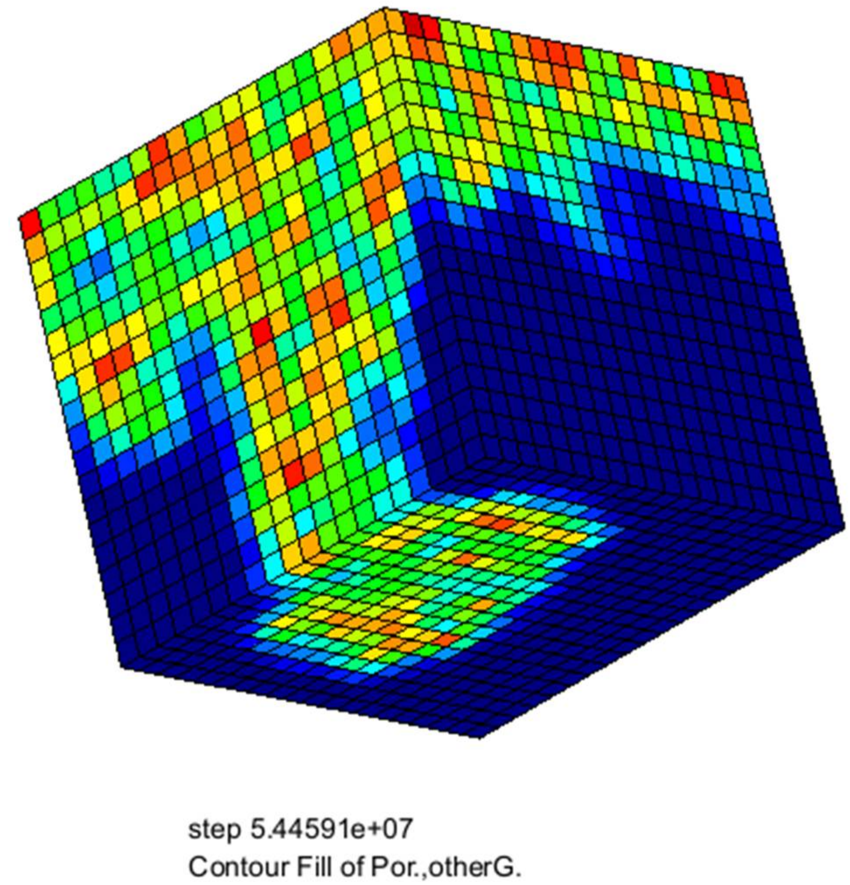
Clique aqui!


X 5
18.914
16.813
14.711
12.61
10.508
8.4064
6.3048
4.2032
2.1016
0

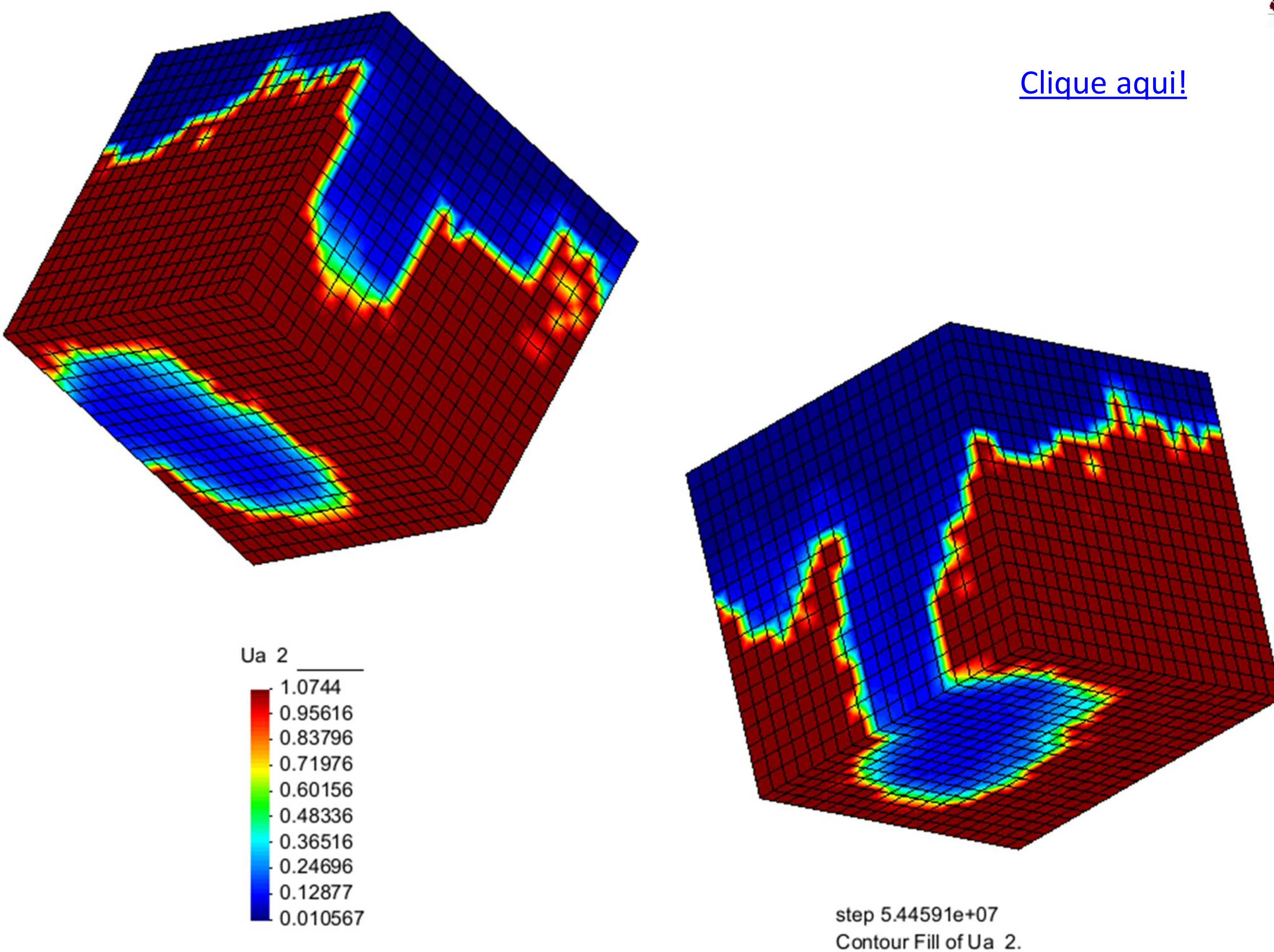

step 5.44591e+7
Contour Fill of X 5.

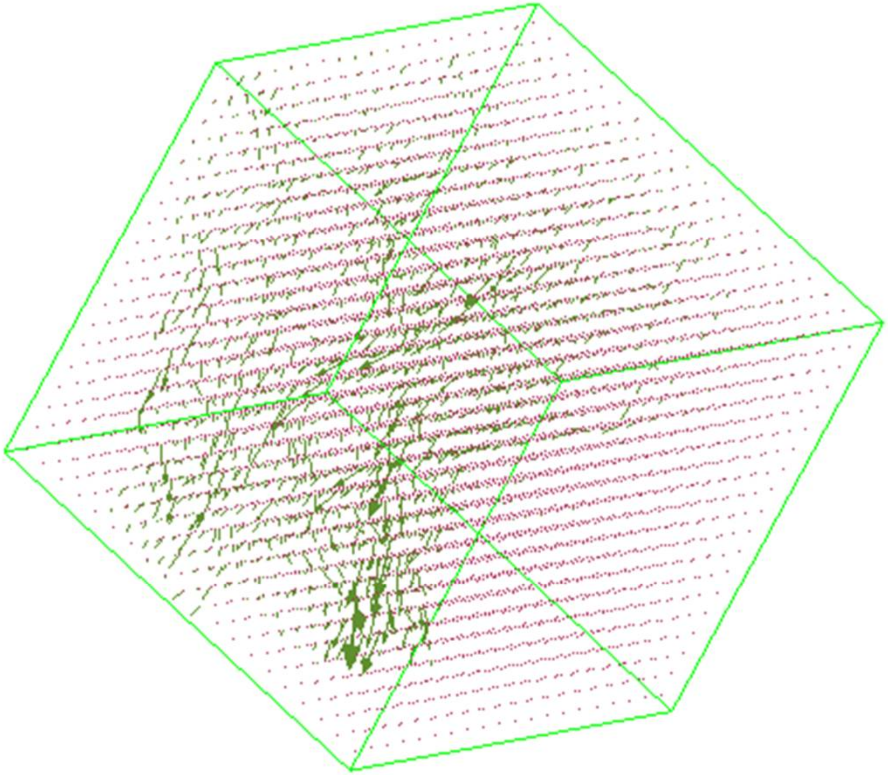

Por.,otherG
0.37671
0.35486
0.333
0.31114
0.28929
0.26743
0.24557
0.22371
0.20186
0.18

[Clique aqui!]

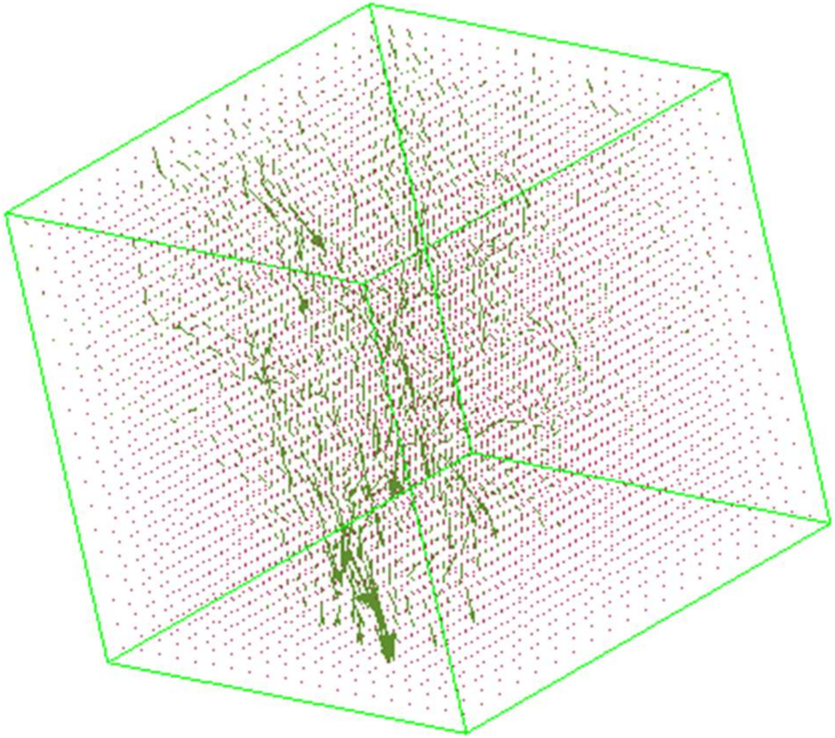

step 5.44591e+07
Contour Fill of Por.,otherG.

Clique aqui!


Ua 2
1.0744
0.95616
0.83796
0.71976
0.60156
0.48336
0.36516
0.24696
0.12877
0.010567
step 5.44591e+07
Contour Fill of Ua 2.



Clique aqui!



HM-C Couplings

Chemo-mechanical constitutive model:

$$\dot{\varepsilon}_{vol}^{che} = \frac{D\varepsilon_{vol}^{che}}{Dt} = \eta \frac{1}{(1-\phi)} \frac{Dv_T}{Dt}$$

Cristal Growth

Chemical compaction

$$v_T = \text{total mineral volume} = \sum_m \bar{v}_m c_m$$

$\bar{v}_m$: molar volume (m^3/mol) of mineral m

c_m : concentration (mol/m^3 of rock) of mineral m

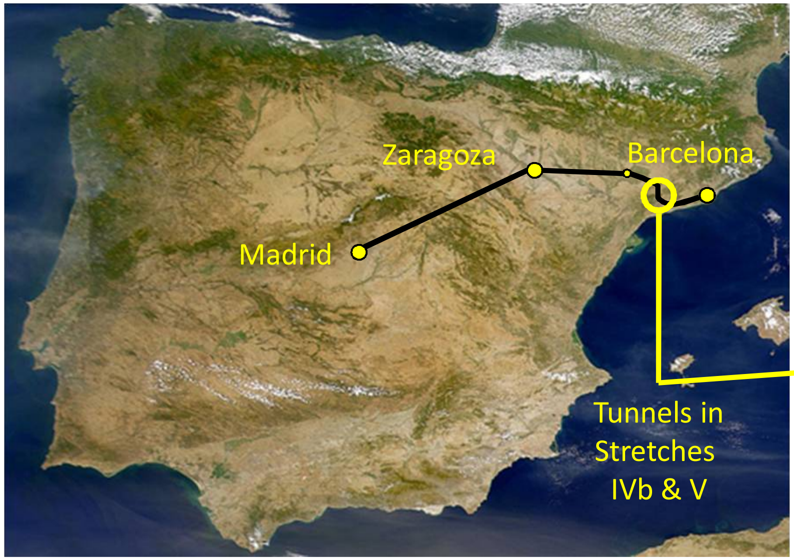
η : parameter

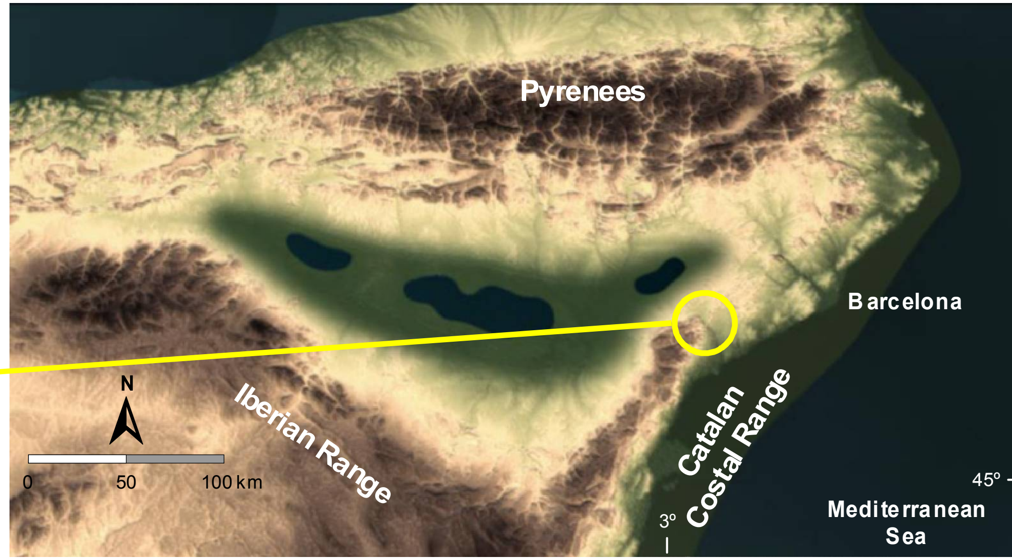
Linear-elastic law including chemical (volumetric) strains:

$$\dot{\sigma} = D_e(\dot{\varepsilon} - m\dot{\varepsilon}_{vol}^{che})$$

Case history: tunnel in sulphate bearing rock

High-speed Railway Madrid –Barcelona





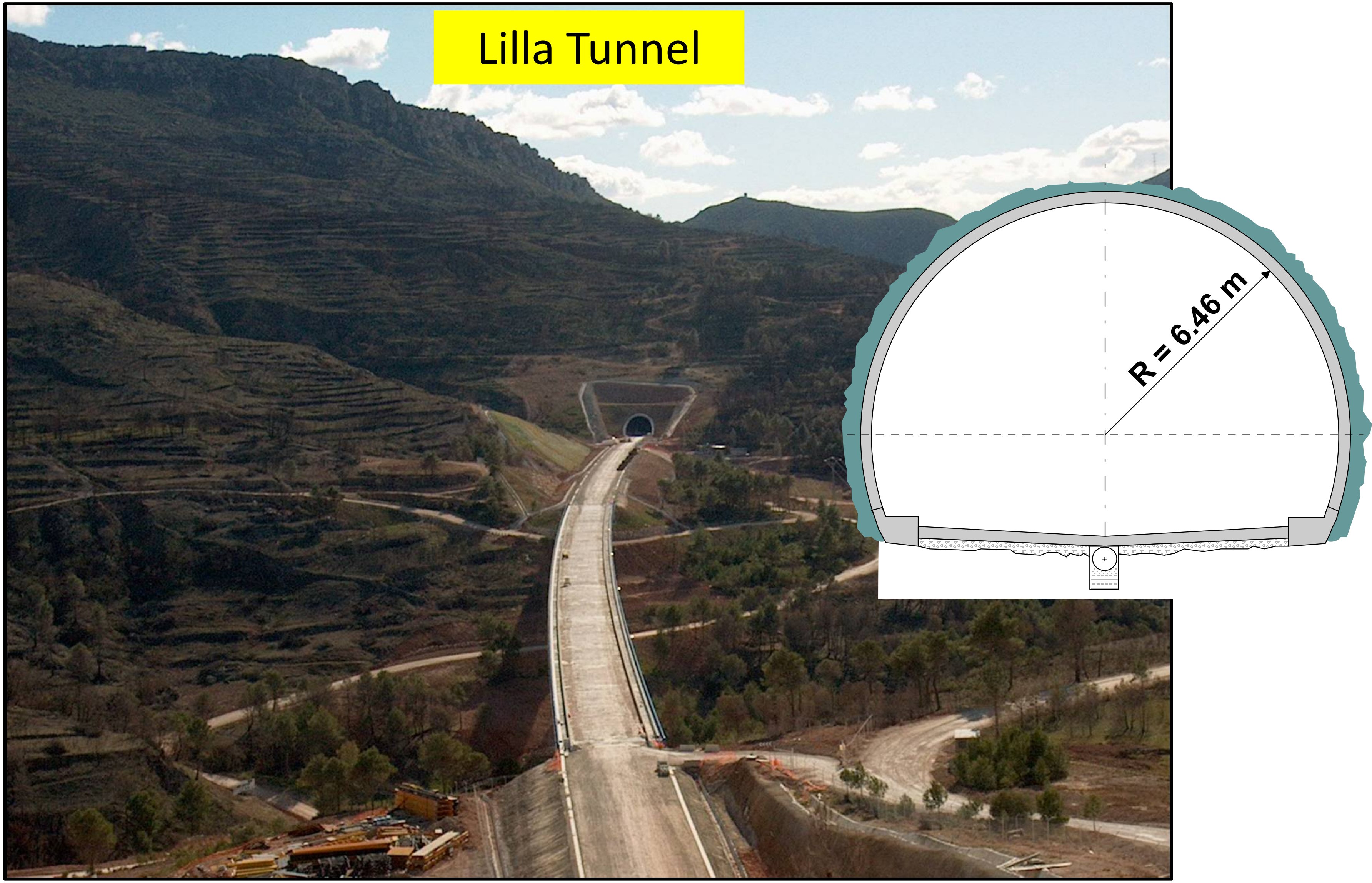
length: 629 km

Railway Authority

Tunnels in Section Lleida-Martorell

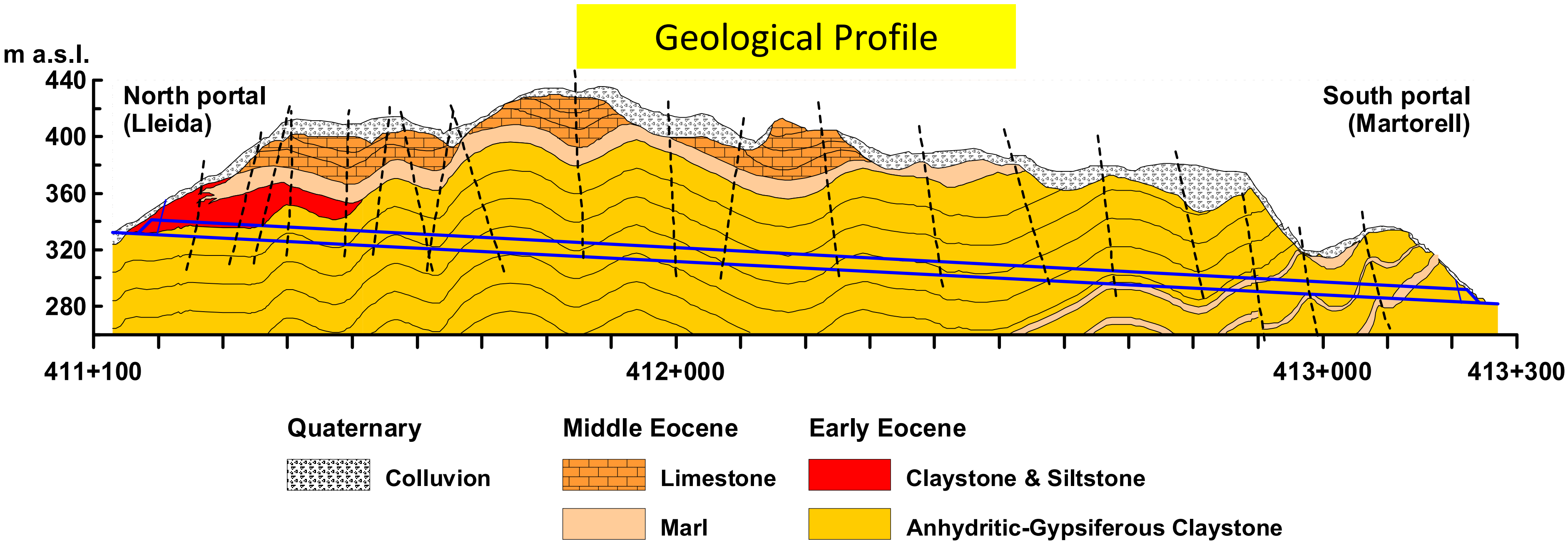
Tunnel	Length (m)	Maximum Cover (m)	Excavated Cross-Section (m^2)
Camp Magre	954	52	140
Lilla	2034	110	117
Puig Cabrer	607	191	137

Case history: tunnel in sulphate bearing rock



- Excavated in 2001-2002 by drill and blast (head and bench) from the two portals

Case history: tunnel in sulphate bearing rock



The Tertiary Anhydritic-Gypsiferous Claystone from the Lilla Tunnel

the excavated material

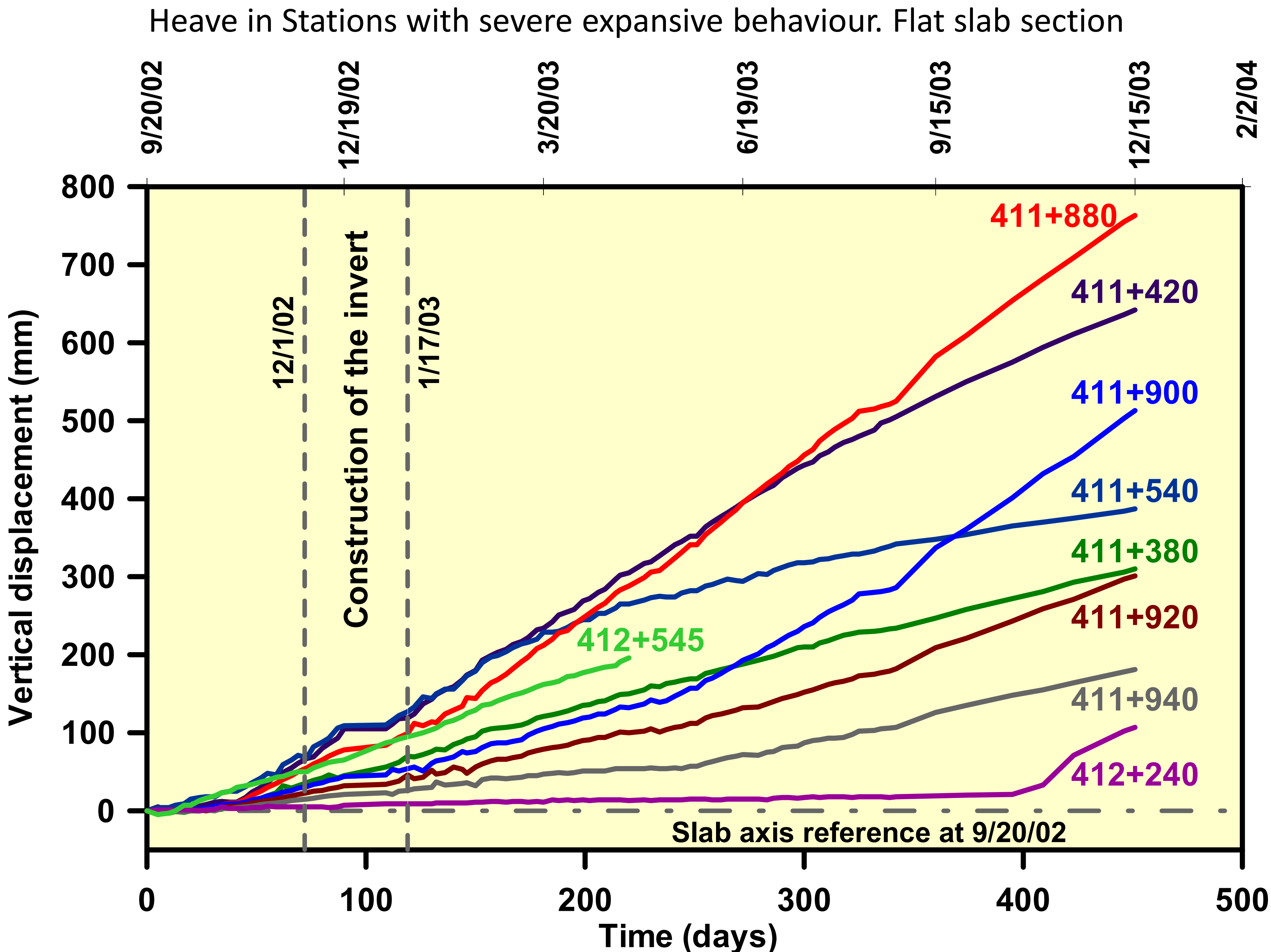
cross-shaped fibrous gypsum veins

slickenside

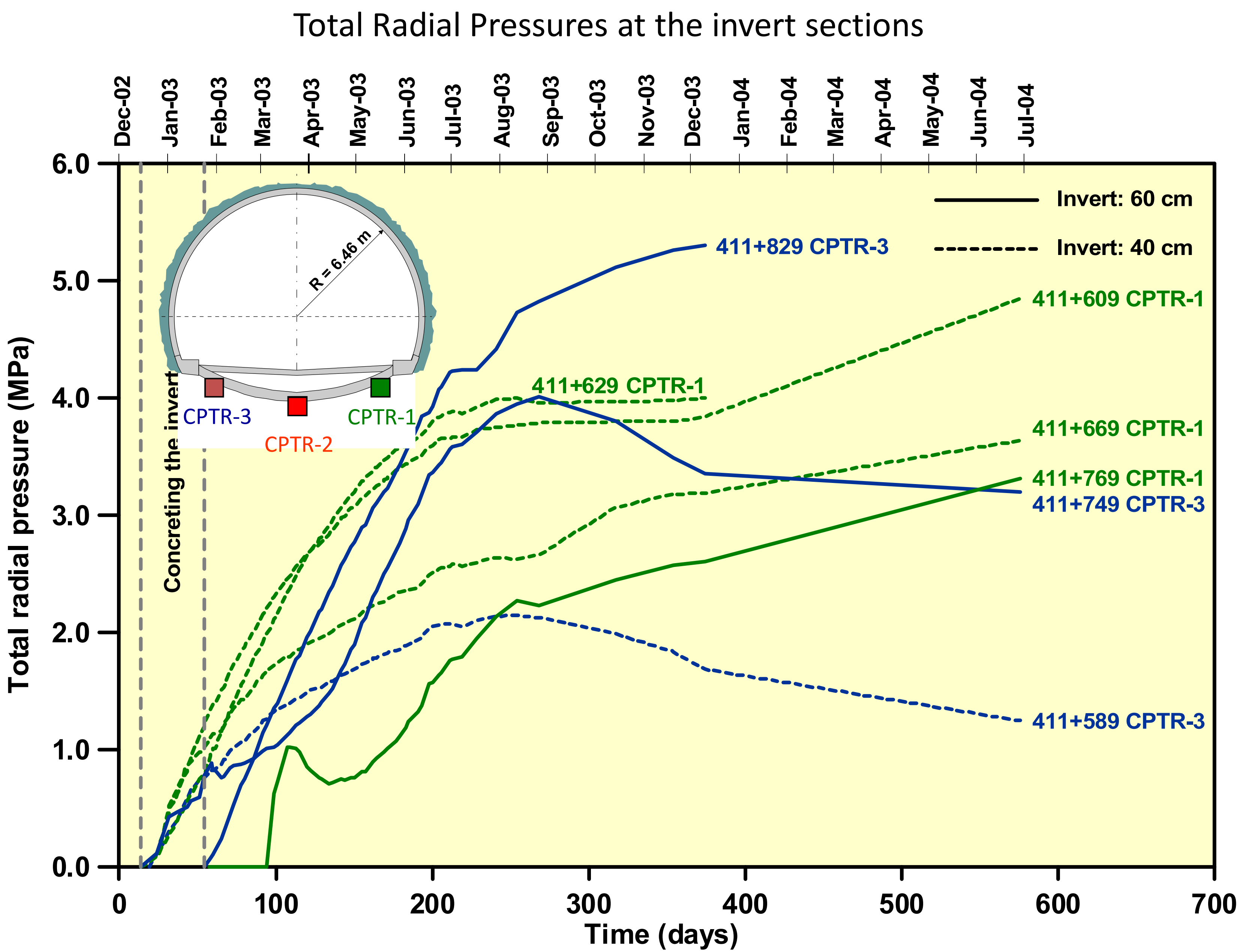
Case history: tunnel in sulphate bearing rock

Heave in the flat slab section

Lilla tunnel: field observations



Lilla tunnel: field observations

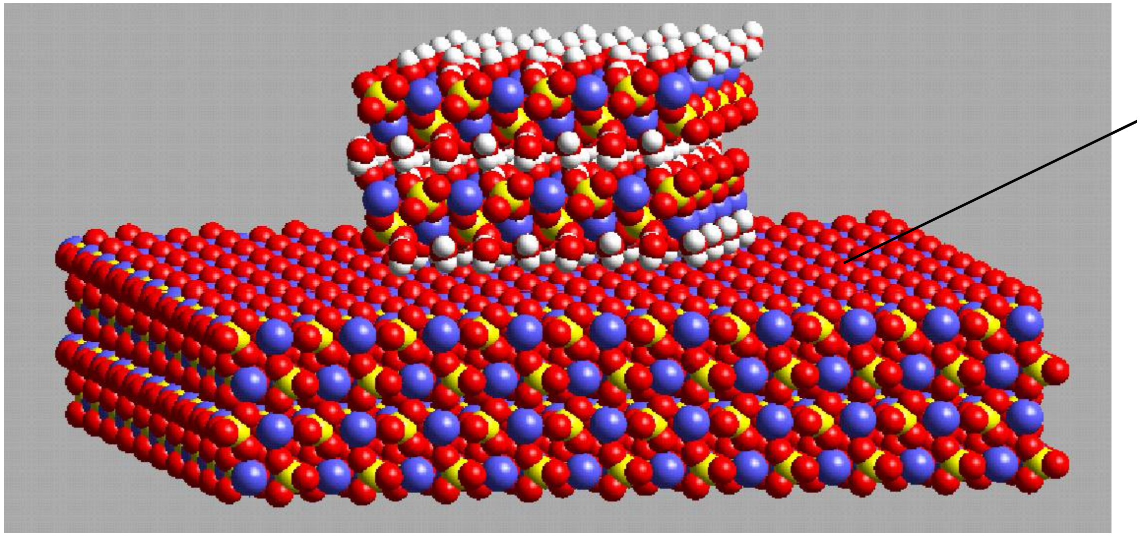


Heave in sulphate bearing rock: analysis

Anhydrite/gypsum system

Anhydrite: $Ca^{2+} + SO_4^{2-}$ Gypsum: $Ca^{2+} + SO_4^{2-} + 2H_2O$

Anhydrite



Gypsum

- The molar volume of gypsum is 62% larger than that of anhydrite
- Direct transformation is apparently not possible
- Conversion from anhydrite to gypsum is via dissolution - precipitation

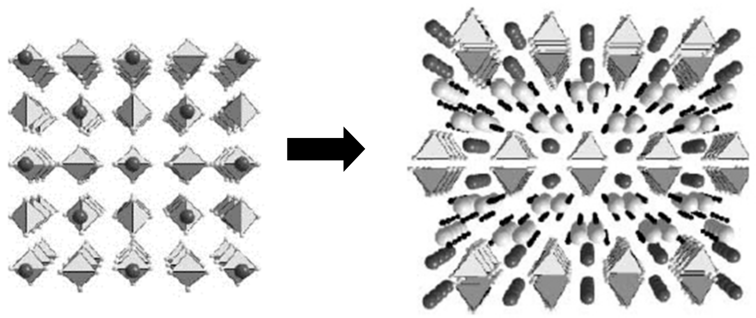
Sulphate-Bearing Clayey Rocks

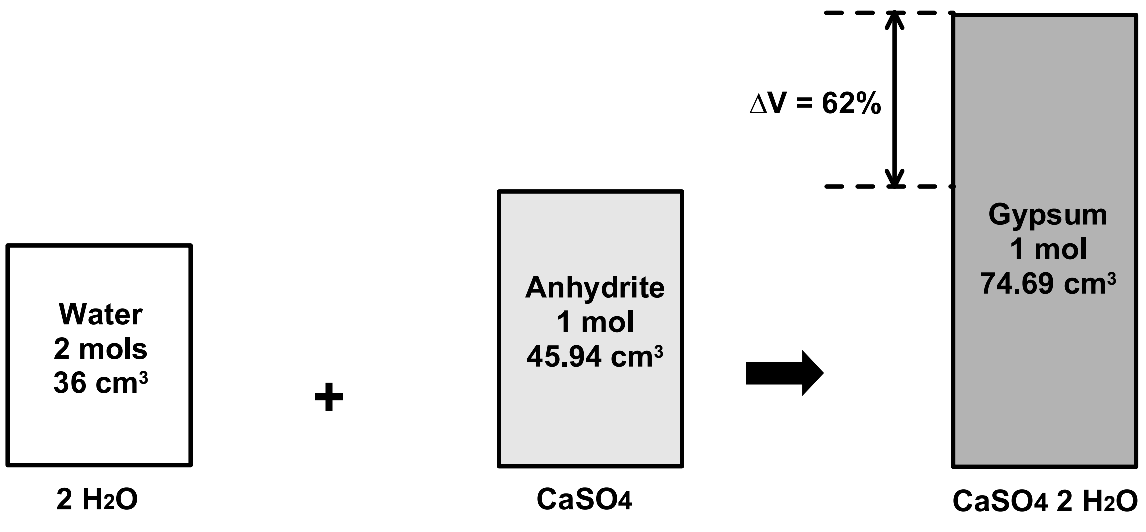
Expansive Behaviour

TRANSFORMATION OF ANHYDRITE INTO GYPSUM IN AN OPEN SYSTEM

Anhydrite: Gs = 2.96

Gypsum: Gs = 2.32





Heave in sulphate bearing rock: analysis

EURO:TUN 2009
2nd International Conference on Computational Methods in Tunnelling
Ruhr University Bochum, 9-11 September 2009
Aedificatio Publishers, 1-4

HMC analysis of a tunnel in swelling rock

Ivan Berdugo[1], Leonardo do N. Guimarães[2], Antonio Gens[3], Eduardo E. Alonso[3]
[1]Department of Civil Engineering, PUJ, Bogotá, Colombia
[2]Universidade Federal de Pernambuco, Recife, Brazil
[3]Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia, Barcelona, Spain

Gens, A. (2010). *Géotechnique* **60**, No. 1, 3–74 [**doi:** 10.1680/geot.9.P.109]

Soil–environment interactions in geotechnical engineering

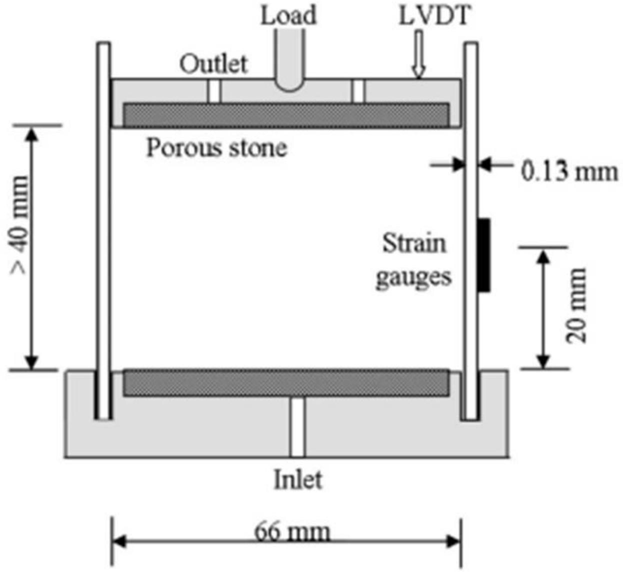
A. GENS*

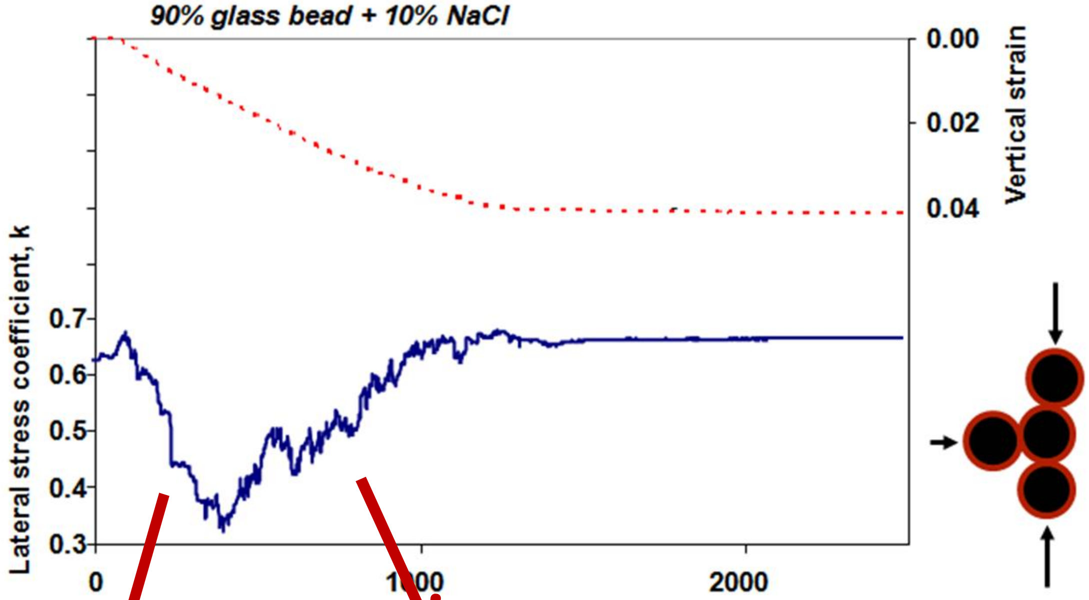
HM-C Couplings

Mineral Dissolution and the Evolution of k_0

Hosung Shin[1] and J. Carlos Santamarina[2]

JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING © ASCE / AUGUST 2009 / 1141





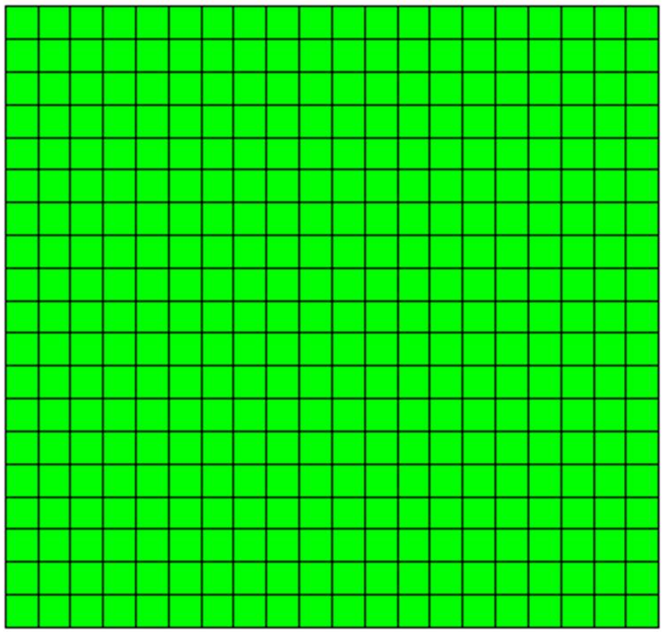
grain mass loss due to mineral dissolution produces a pronounced horizontal stress drop under zero lateral strain conditions

rearrangement of the internal granular structure (discrete element simulation results confirm that the internal friction is fully mobilized at kmin)

3D PLUG MODEL

Sample dimensions: 10x10x10cm

Injection of an under-saturated water



Pressure at the top: $P + \Delta P$; ΔP =0.1MPa

Dissolution front of mineral

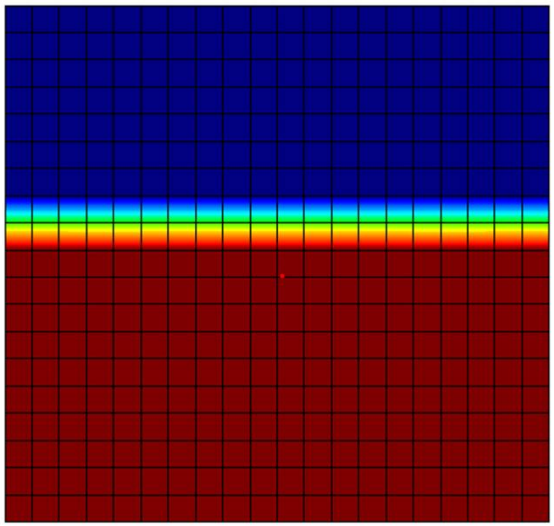
Pressure at the bottom: P

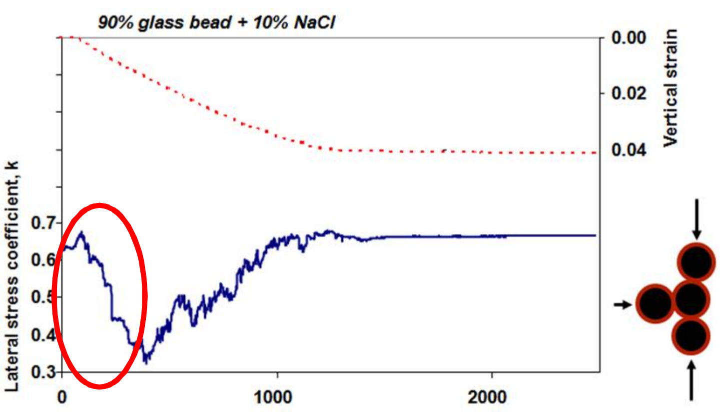
Initially:

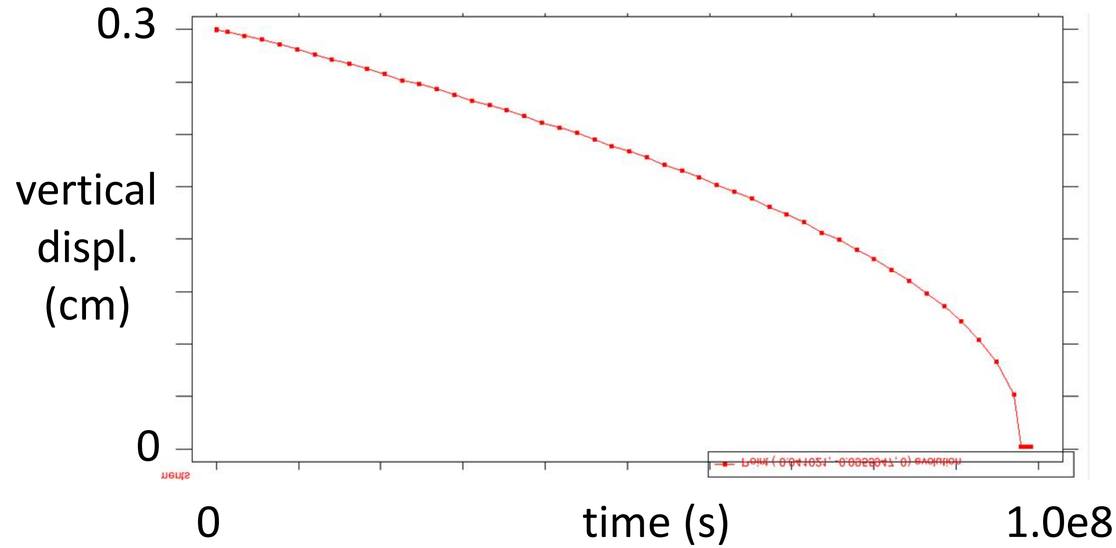
- porosity and permeability: constants

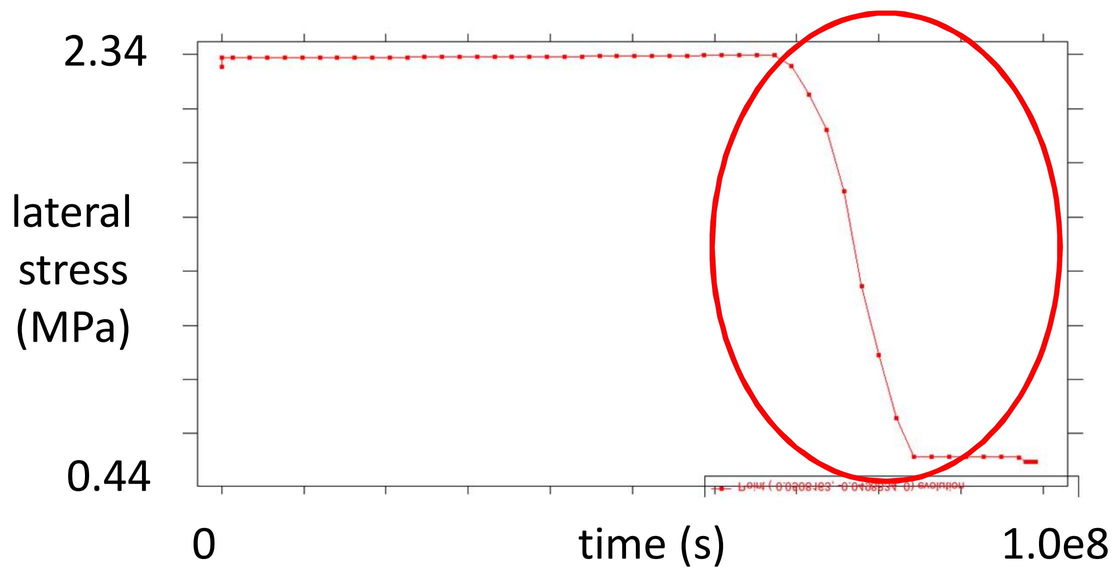
HM-C Couplings

Constant initial mineral concentration distribution



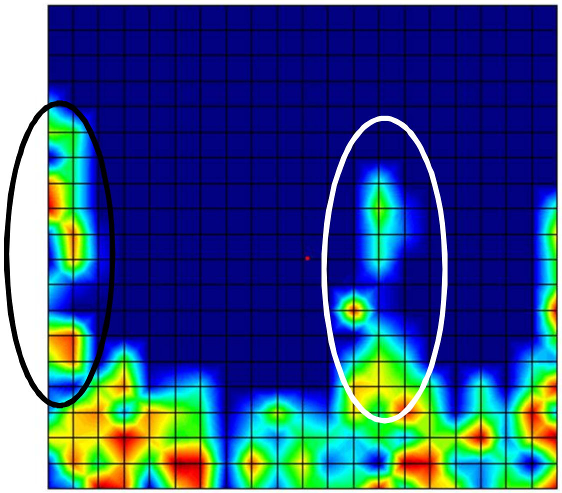


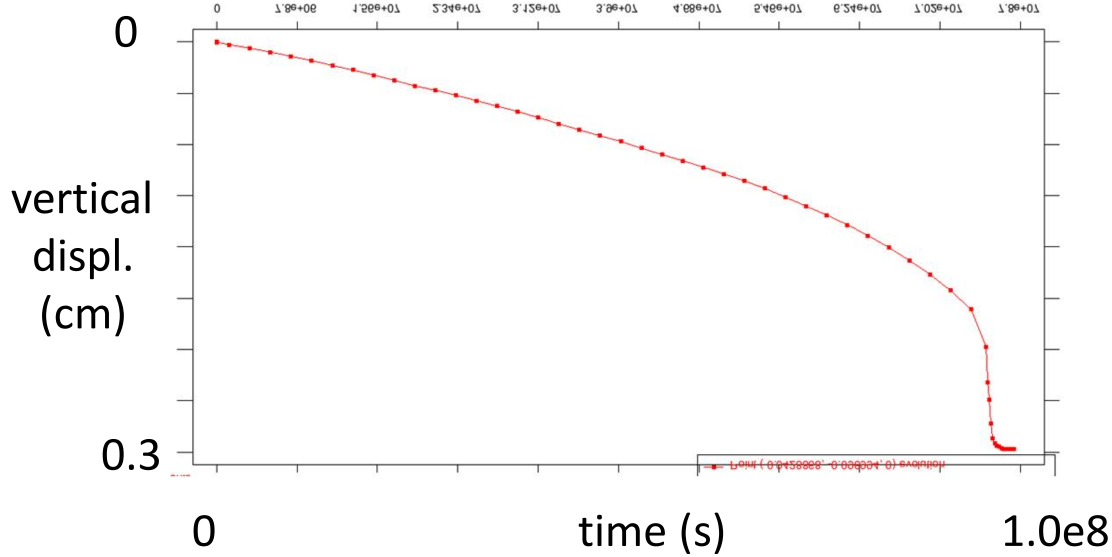




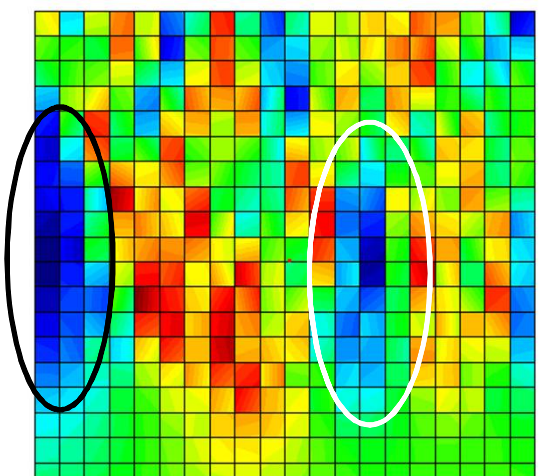
HM-C Couplings

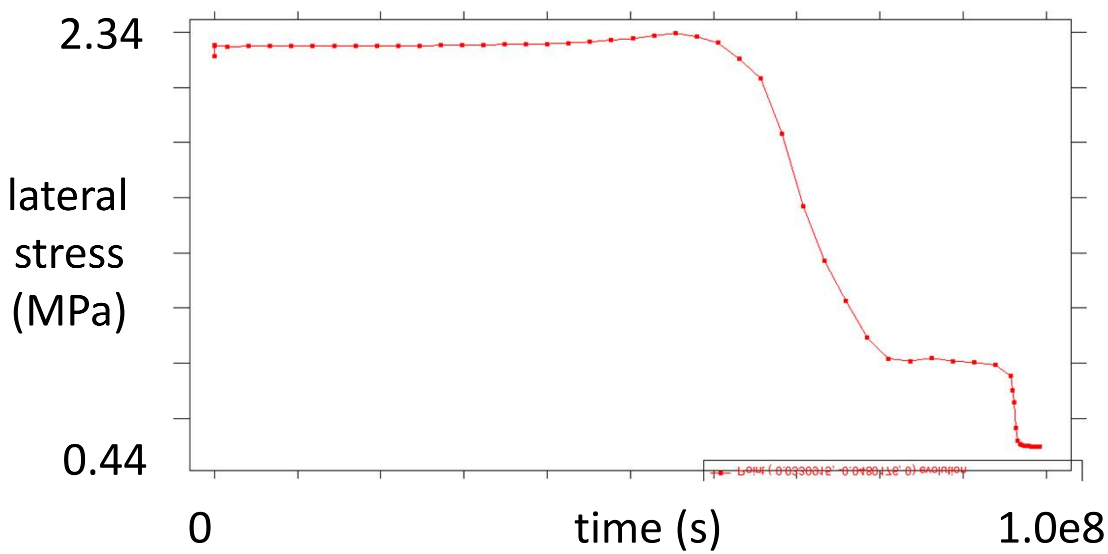
Randomic initial mineral concentration distribution





Higher vertical stresses in remaining mineral zones

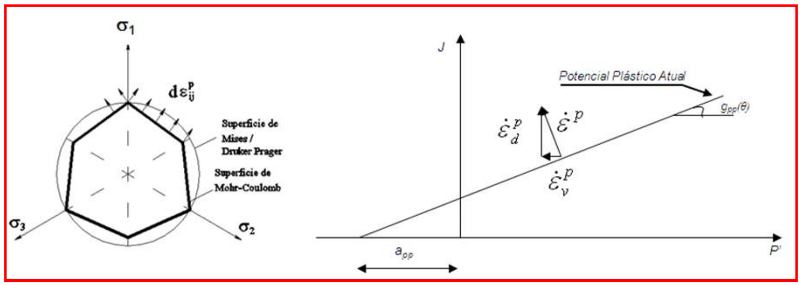


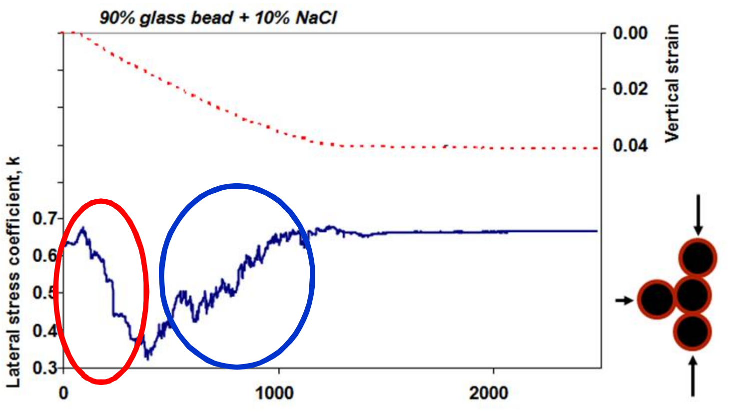


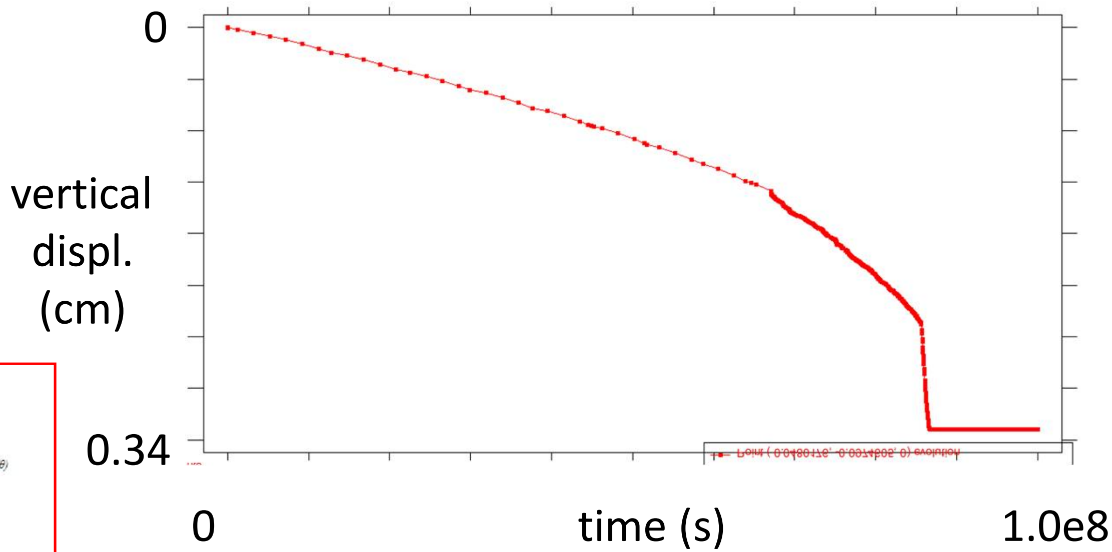
HM-C Couplings

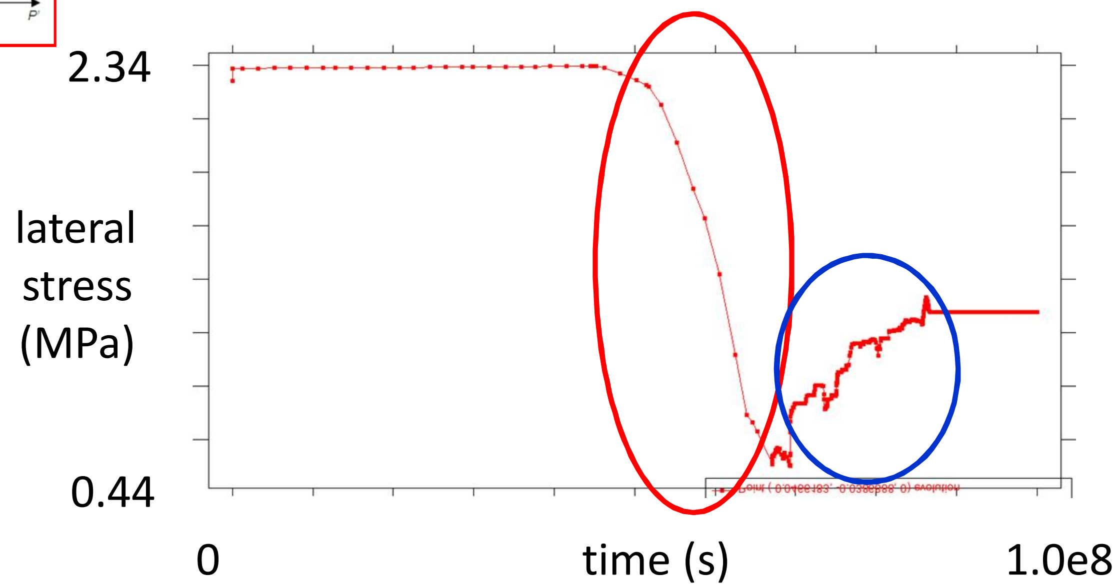
Assuming elastoplastic Mohr-Coulomb law:

$$\dot{\sigma} = D(\dot{\varepsilon} - \dot{\varepsilon}^{p} - m\,\dot{\varepsilon}^{che}_{vol})$$



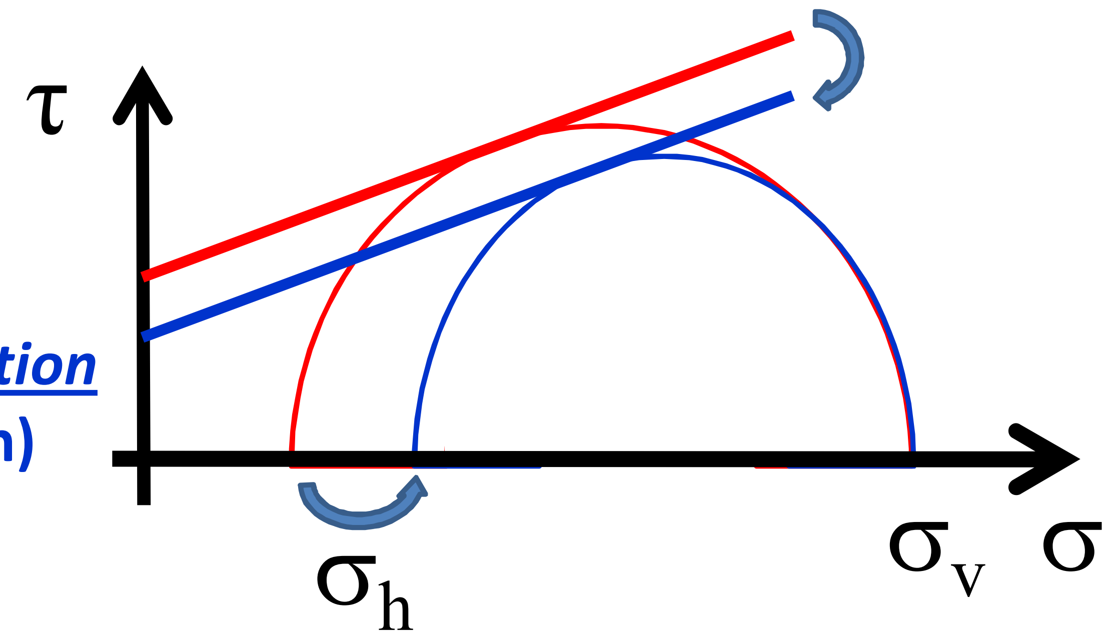




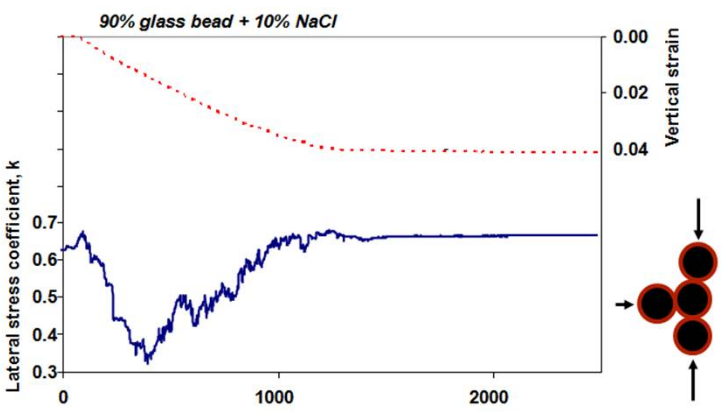


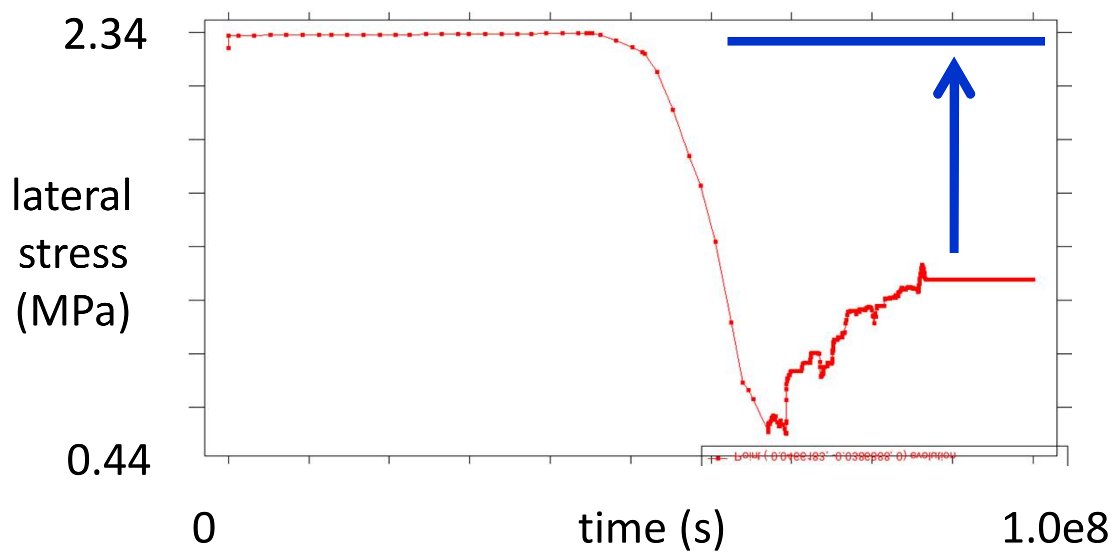
HM-C Couplings

How to increase
the lateral stress??



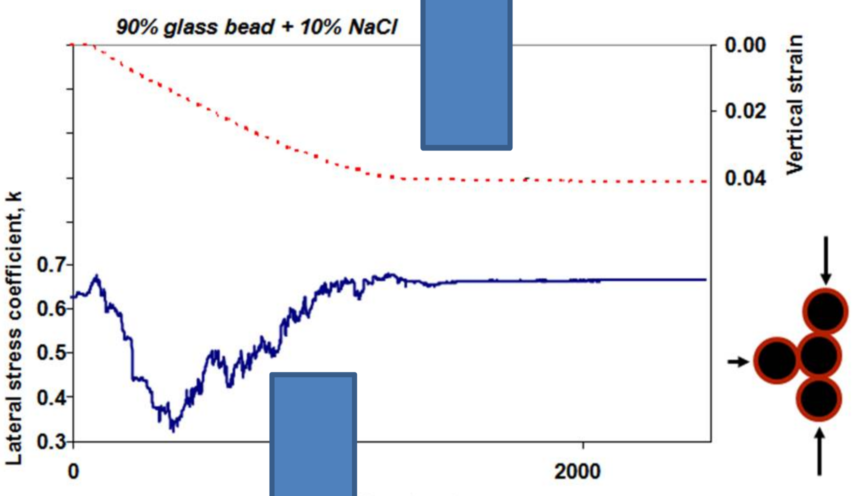
Introducing *material degradation*
(eg., decreasing of cohesion)



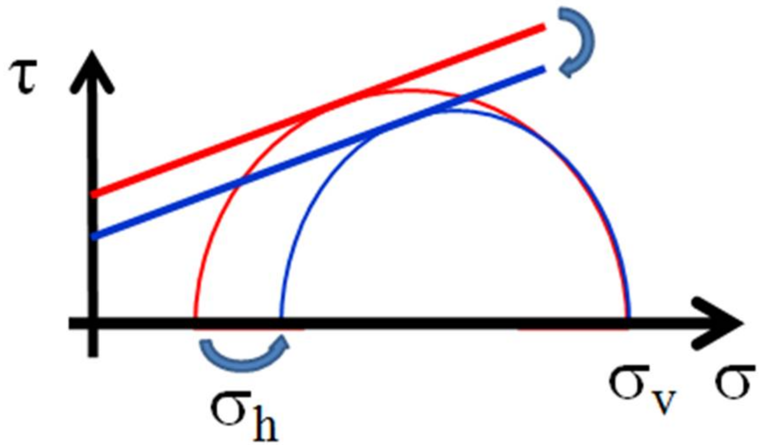


At well and reservoir scales...

Cement dissolution under load can cause:



Chemically Induced Reservoir Compaction



Material degradation (decreasing of shear strength):

- Wellbore stability
- Faults...

CONCLUSIONS

► **A numerical tool capable to evaluate the integrity of reservoir and cap rocks has been presented considering a number of HM and HMC phenomena.**

► **Consideration of chemical effects requires the incorporation of:**

- **New (environmental) variable: concentration of chemical species**
- **New balance equation: reactive transport equation**
- **Chemical models accounting for kinetics and chemical equilibrium are required**

► **Mineral concentration was adopted as a state variable of a simplified chemo-mechanical constitutive model that was able to reproduce qualitatively deformations induced by cement dissolution.**