Anisotropic permeabilities evolution of reservoir rocks under pressure:

New experimental and numerical approaches

(1)

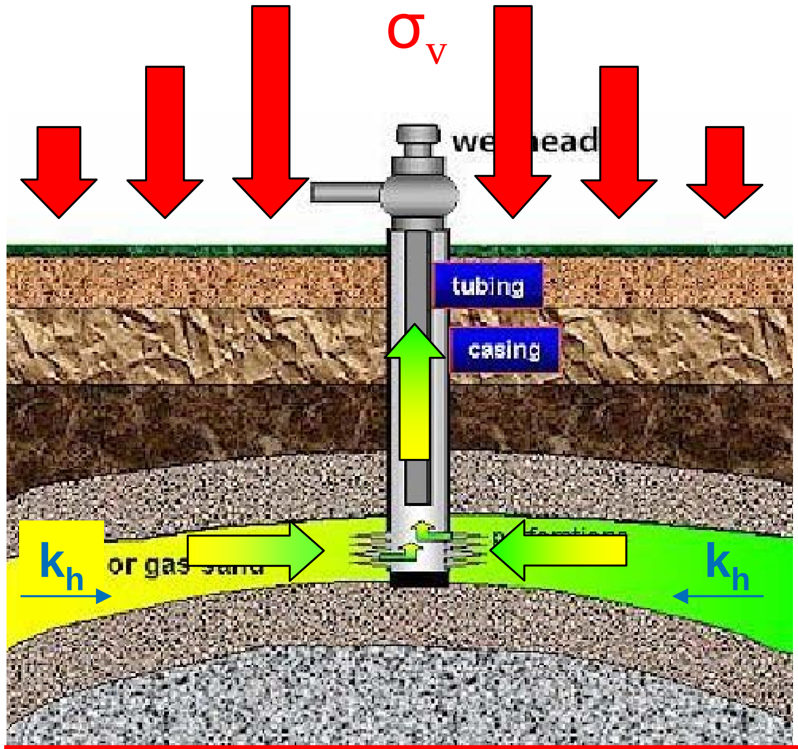
Dautriat J.[1-2*], *Gland N.*[2], *Dimanov A.*[1], *Youssef S.*[2], *Vizika O.*[2]

* Corresponding author: jeremie.dautriat@ifp.fr

Innovation Energy Environment (2)

Context of our study :

Reservoir permeability drop due to compaction during the production



- Primary recuperation ⟶ Pore Pressure P_p decreases
- Effective stresse increases

$$\sigma_{eff} = \frac{2\sigma h + \sigma v}{3} - Pp$$

- Effective vertical stress increases (dependent of the distance to the borehole)
- Horizontal permeability dependency of the production

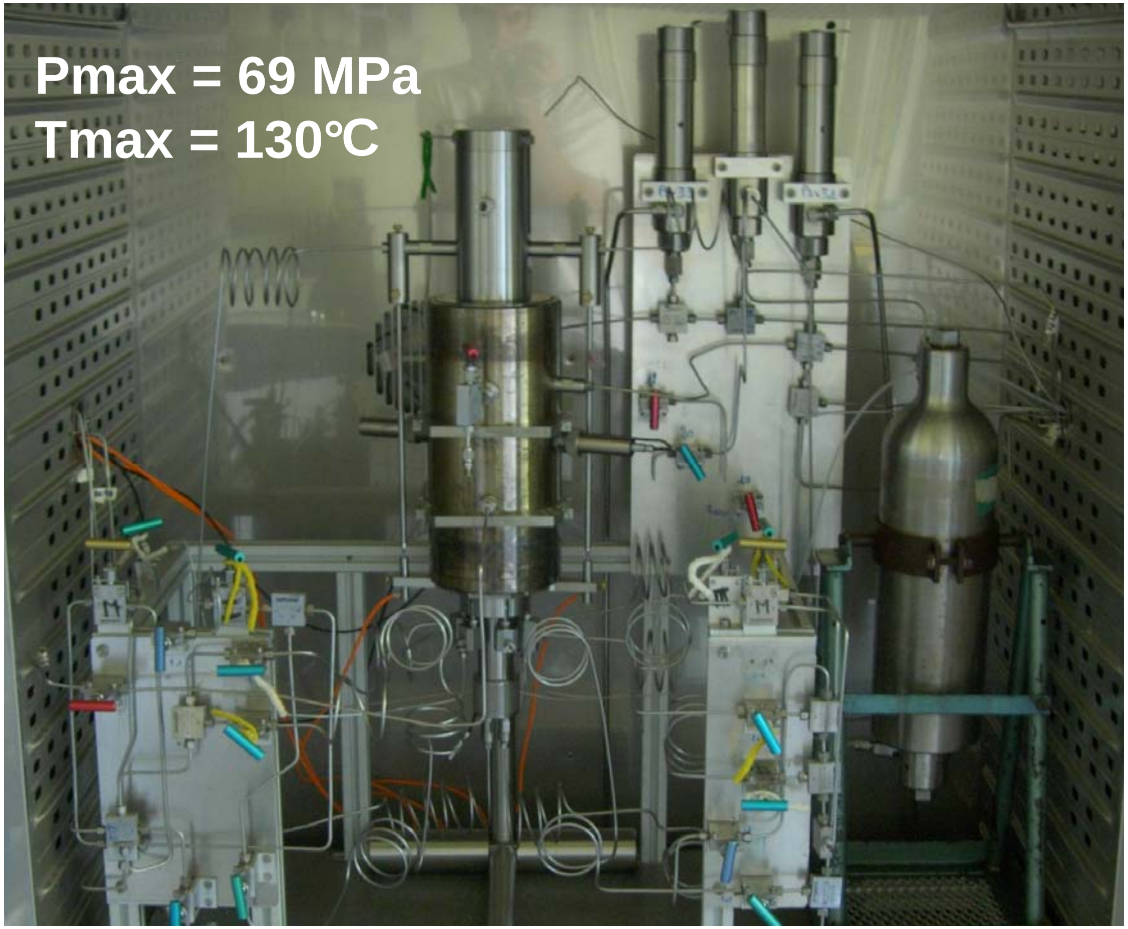
Motivations :

Relation between the evolution of the stress field anisotropy and the transport properties anisotropy ?

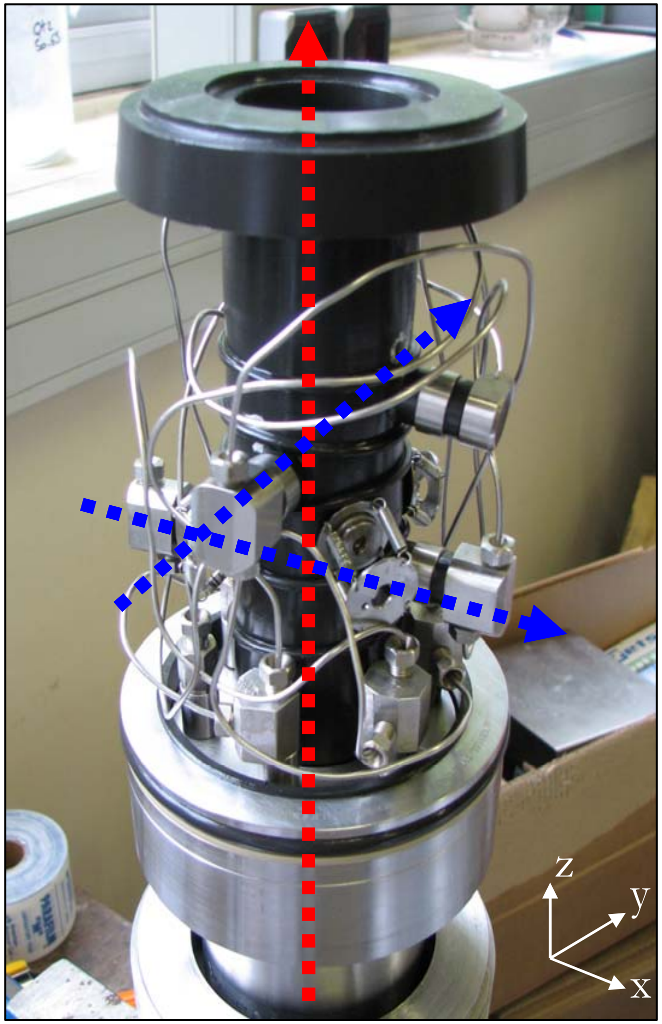
Effects of the stress path on reservoir compressibility ? → Reservoir simulation

EXPERIMENTAL SET-UP

Triaxial cell specially designed to directional permeabilities measurements



Special Core sleeve equipment



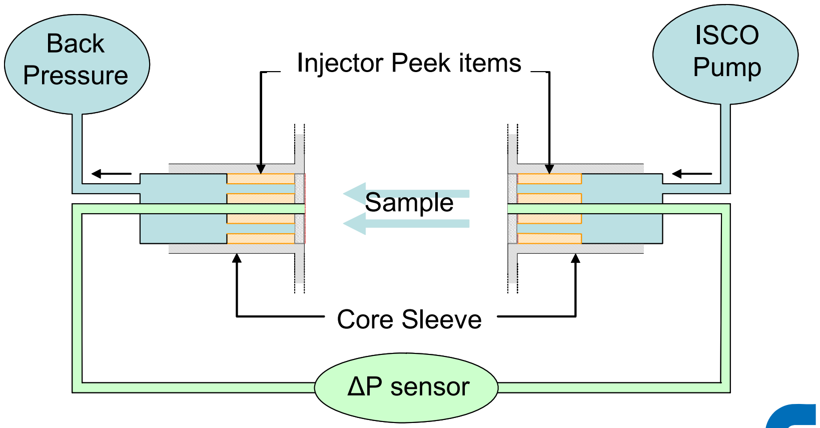
Tridirectional Permeabilities:

Axial permeability measurements: $k_{az,FL}$ & $k_{az,ML}$

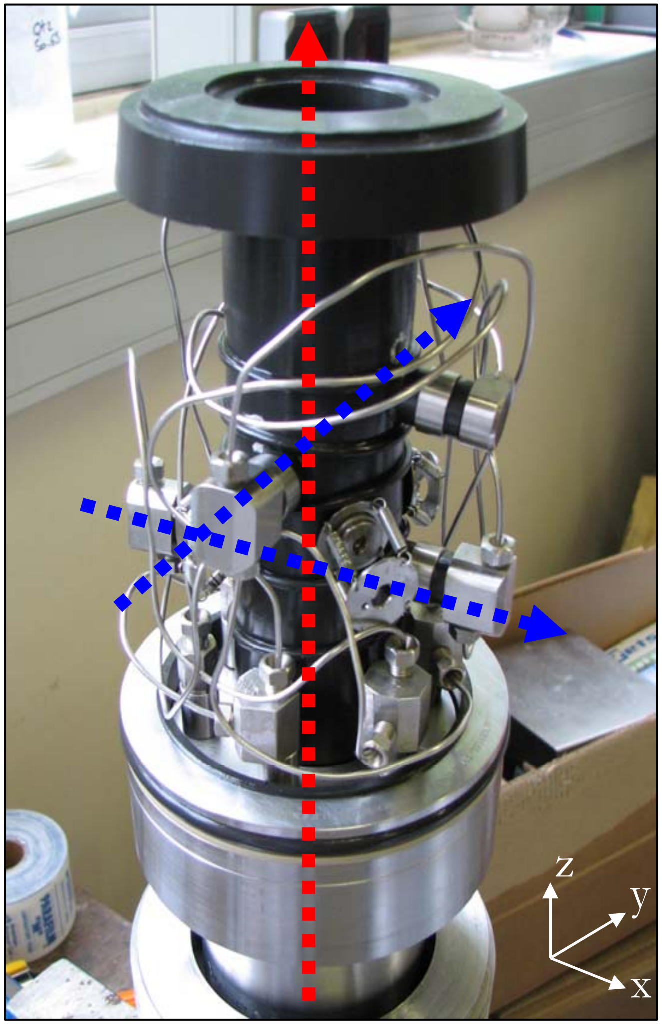
- Classical between inlet and outlet of the sample
- Pore pressure sampling at the mid-length of the sample

Radial permeability measurements: k_{rx} & k_{ry}

- 2 pairs of injector/receptor at the contact of lateral sample surface.



Special Core sleeve equipment



Tridirectional Permeabilities:

Axial permeability measurements: $k_{az,FL}$ & $k_{az,ML}$

- Classical between inlet and outlet of the sample
- Pore pressure sampling at the mid-lenght of the sample

Radial permeability measurements: k_{rx} & k_{ry}

- 2 pairs of injector/receptor at the contact of lateral sample surface.

Complementary measurements:

Sample strains:

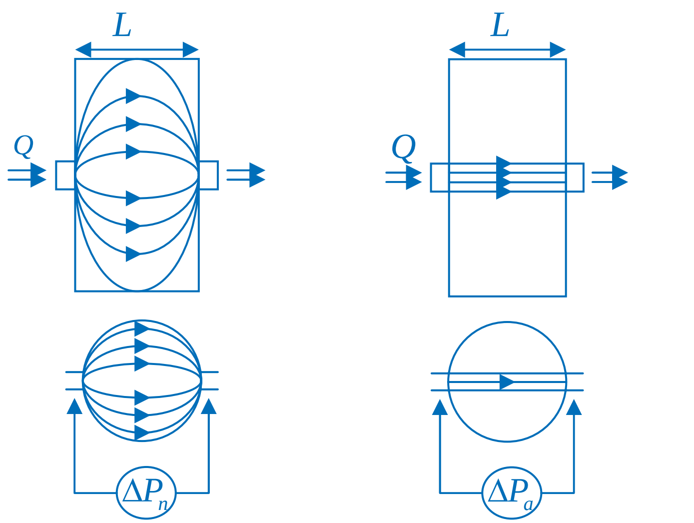
- Axial displacement of the upper piston : external LVDT
- Radial strains : Cantilever fixed on the core sleeve

Porosity Evolution:

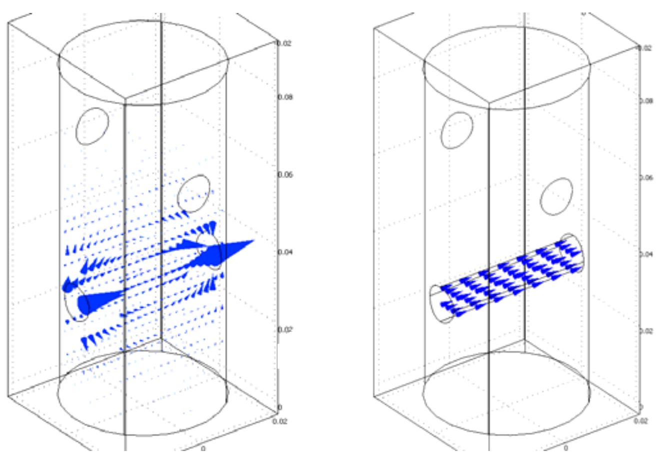
- ΔV_p recorded by ISCO Pump during each confining pressure increase.

Modified Darcy law:
Geometric Factor Calculation using Finite Elements Method

Description of the problem



FEM Contribution



Modified Darcy law : $\dfrac{Q}{A_a} = -G \dfrac{k_r}{\mu} \dfrac{\Delta P}{D}$

True radial flow

$$Q_n = A_n \frac{k_n \Delta P_n}{\mu D}$$

↓ Effective cross-section Area

Equivalent Darcy flow

$$Q_a = A_a \frac{k_a \Delta P_a}{\mu D}$$

↓ Injector Area

Considering an isotropic permeability case :

Geometric factor $G = \dfrac{A_a}{A_n} = \dfrac{\Delta P_n}{\Delta P_a}$

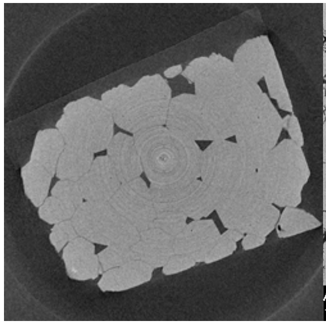
FEM simulation → $G = 0.18$

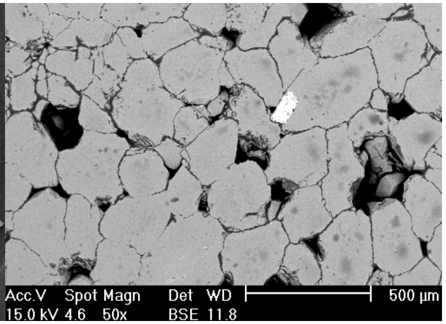
Bai & al. SPE#78188 (2002)

EXPERIMENTAL RESULTS

Tested Samples

Fontainebleau Sandstones:

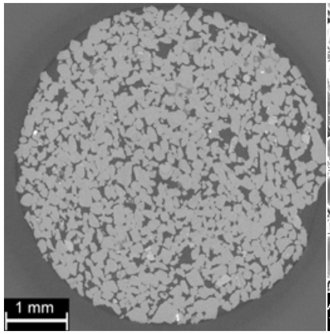


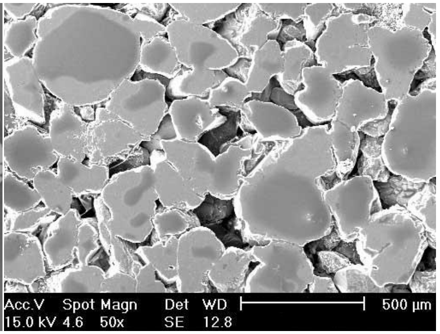


Porosity: 5.4 to 8% **Permeability: 2.5 to 30mD**

→ Hydrostatic loading

Bentheimer Sandstones:

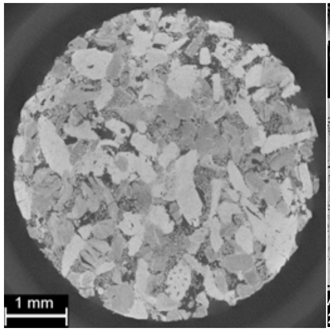


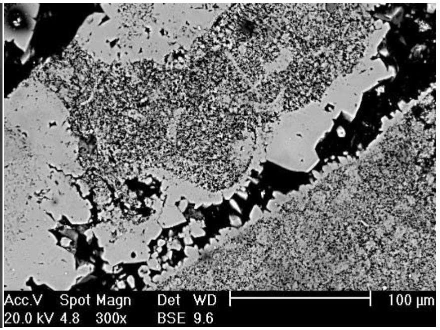


Porosity: 24% **Permeability: 3000 mD**

→ Hydrostatic and Deviatoric loading at low confining pressure

Estaillades Limestones:



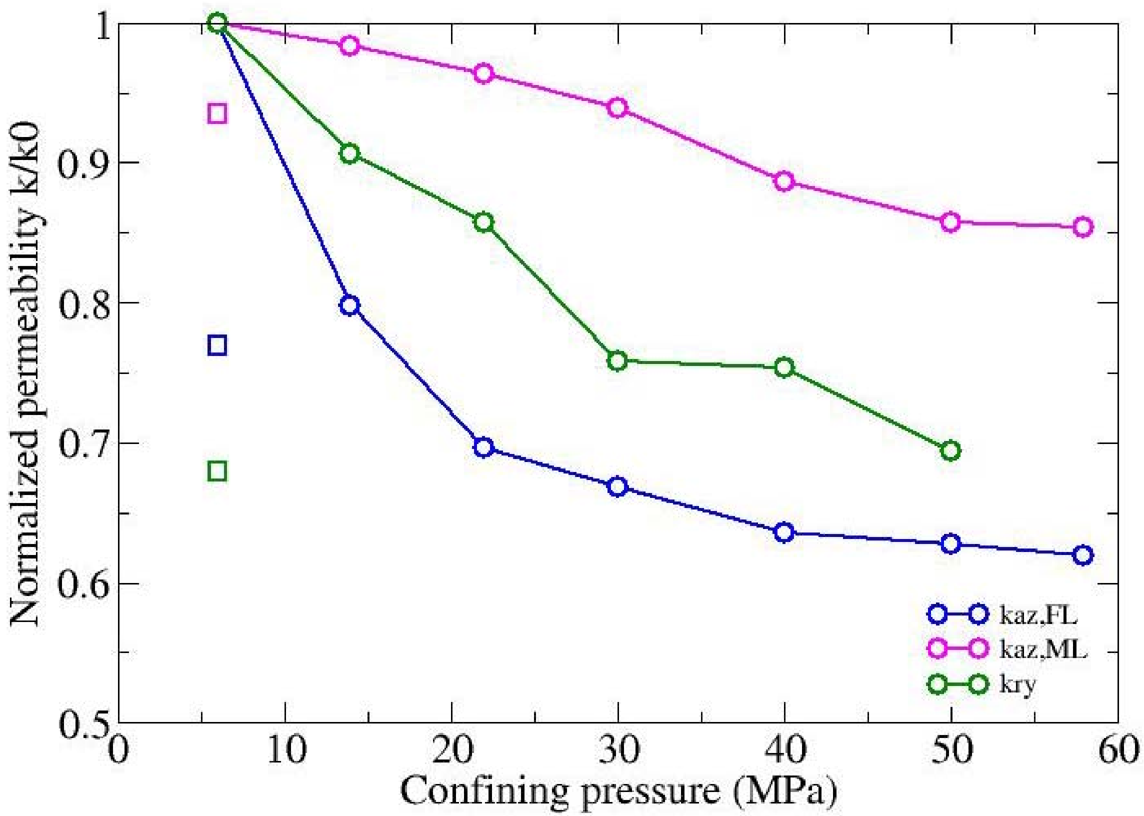


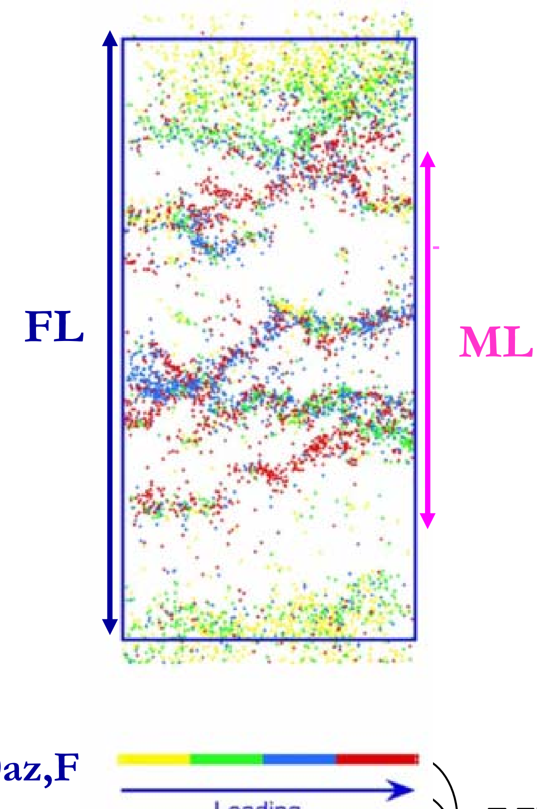
Porosity: 27% **Permeability: 150mD**

→ Hydrostatic and Deviatoric loading at low confining pressure

Experimental results : Low permeability sandstone (Fontainebleau)

HYDROSTATIC LOADING **SAMPLE 1 : $\phi = 5.4\%$**





$k_{0az,F}$

$k_{0az,ML}$

$k_{0ry} = 4.8$ mD

x2

Fortin et al.(2006) *JGR*

Ref: David C.(1993) *JGR*; Korsnes et al.(2006) *Tectonophysics*

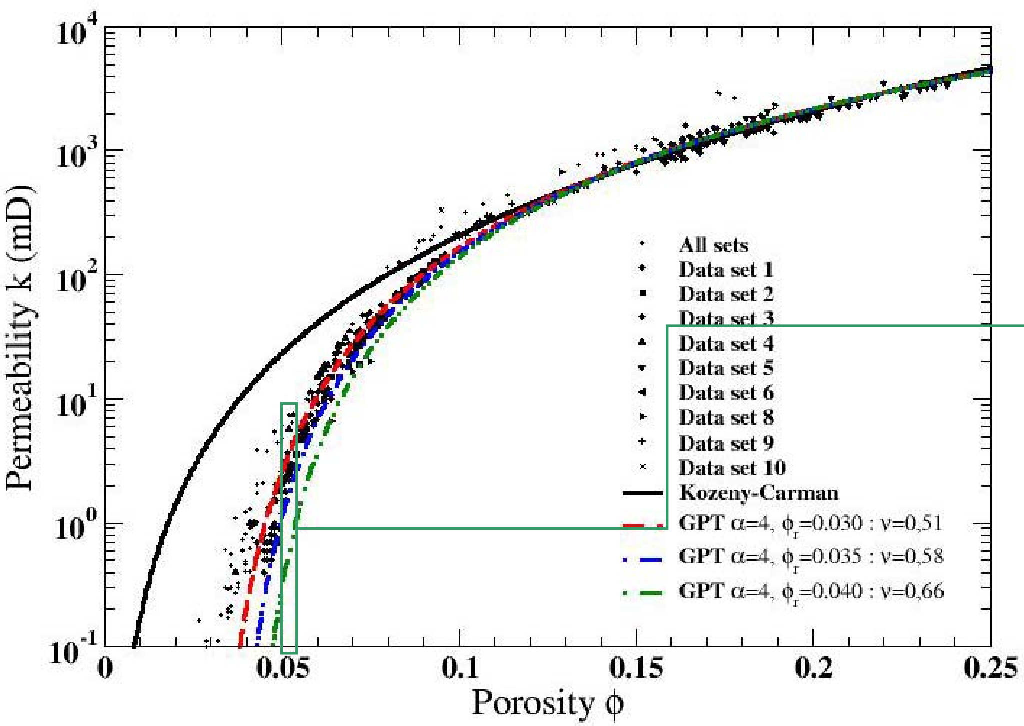
Experimental measurements validation on Fontainebleau sandstones

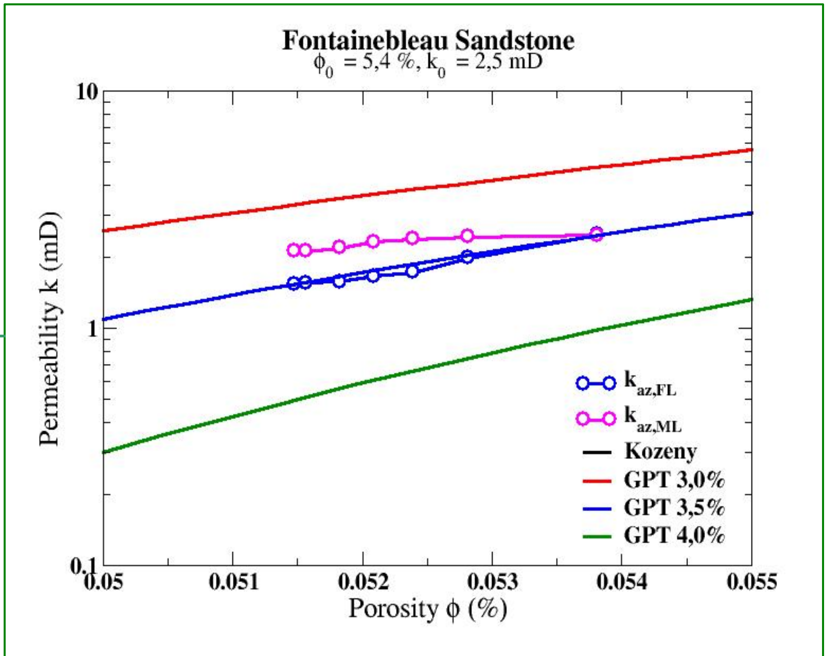
Confrontation of measured k-ϕ and a model of diagenetic compression of Quartz aggregates

Grain Pore Throat Model*

$$k \propto \left(\phi^{1-\upsilon} - \phi_r^{\;1-\upsilon}\right)^4$$

ϕ_r : Residual Porosity; υ : Geometrical Exponent defined as $S \propto \phi^{\upsilon}$

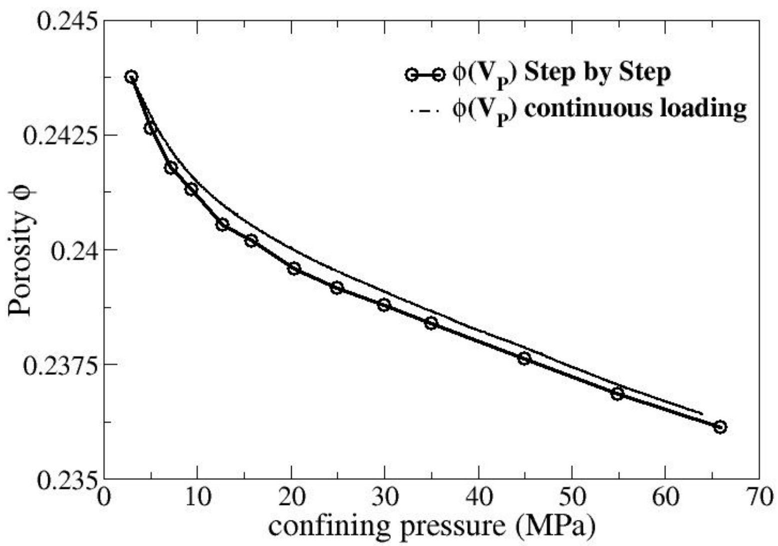


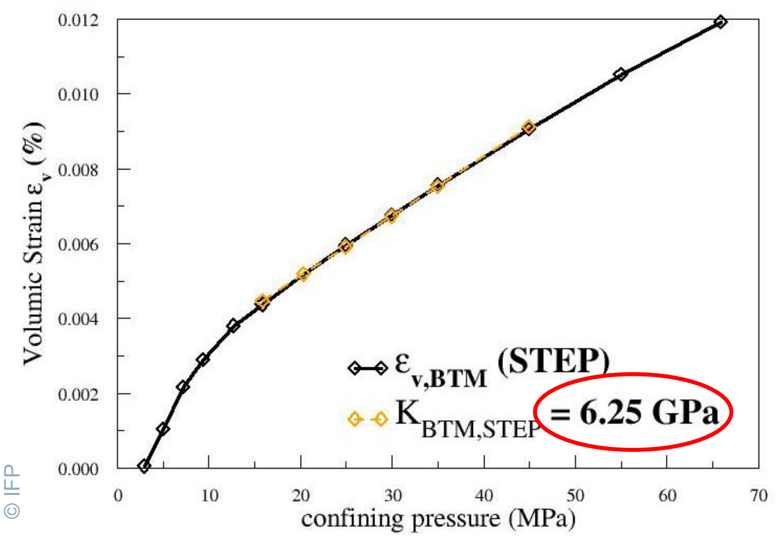


→ **Verified for 3 Fontainebleau Samples (low porosity and low permeability)**

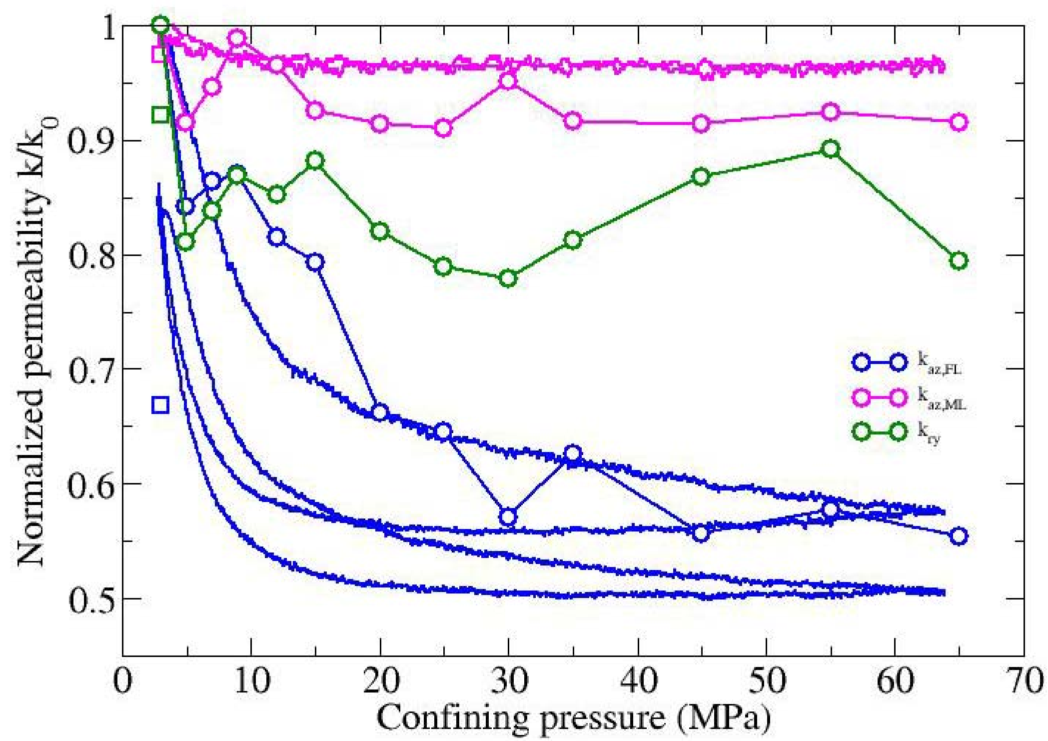
* Chauveteau G. (2002) *SPE#73736*

Experimental results : High permeability sandstone (Bentheimer)





HYDROSTATIC LOADING

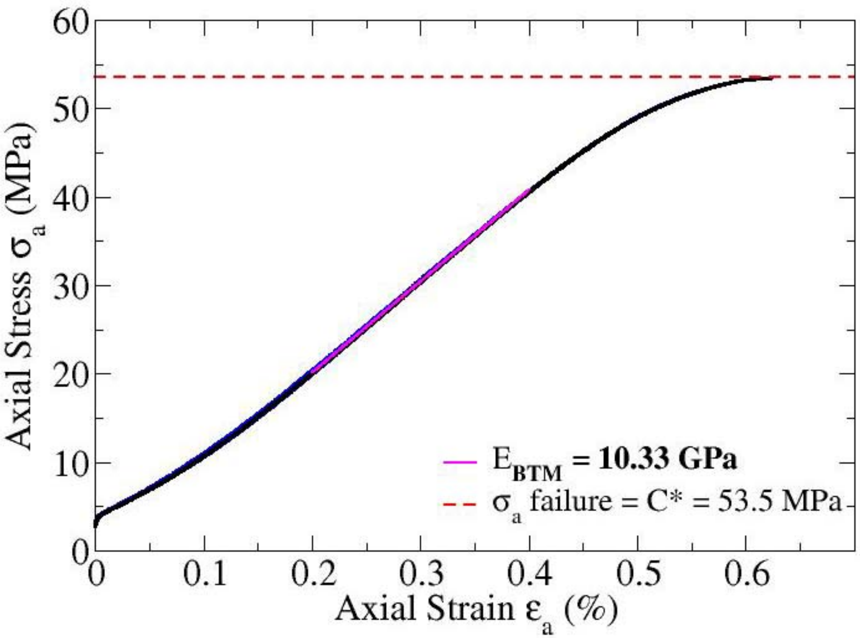


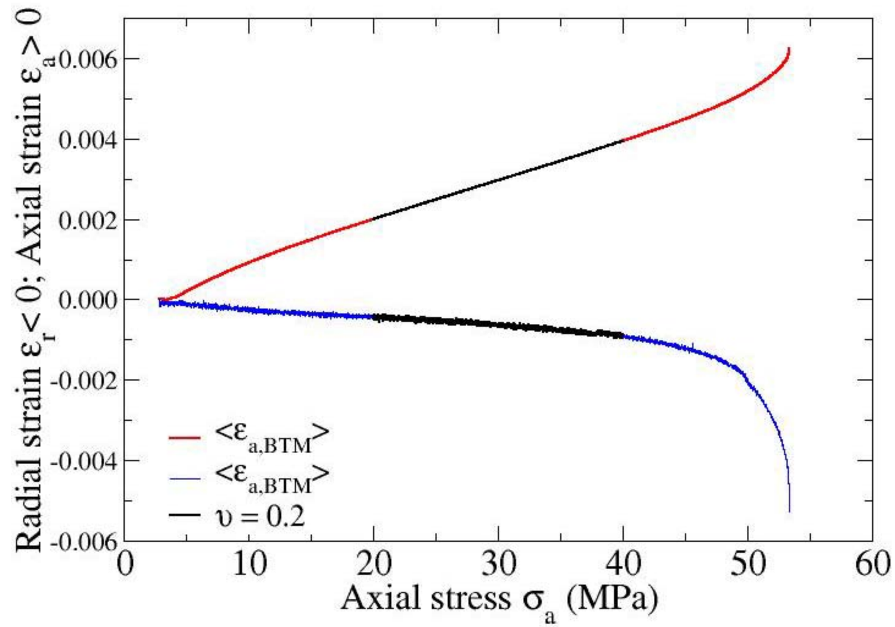
$k_{0az,FL}$ = 1840 mD ; $k_{0az,ML}$ = 2900 mD

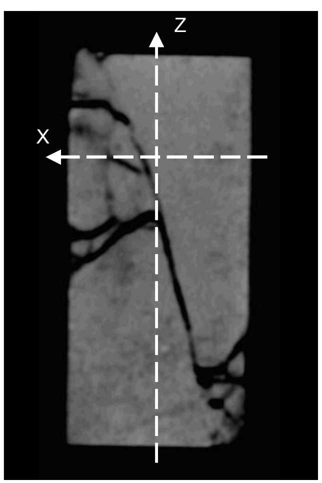
k_{0ry} = 2825 mD

Innovation Energy Environment

« UNIAXIAL » LOADING







Brittle failure: σ_a = **53.5 MPa**

Effective Elastic moduli calculated in the range of axial stress [20:40] MPa :

E = 10.3 GPa
υ = 0.2

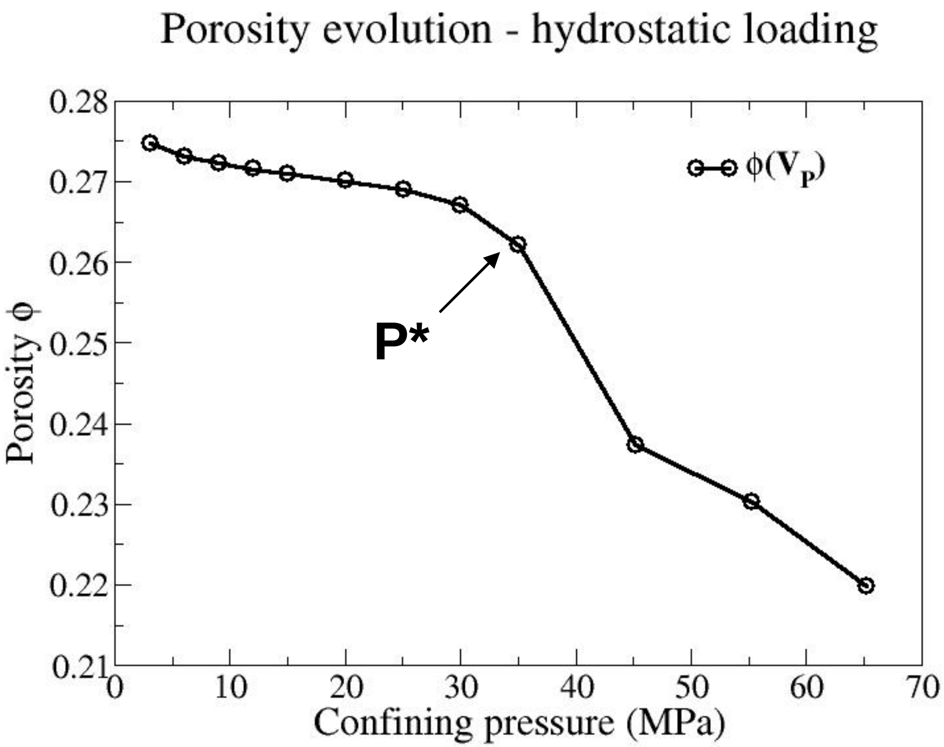
Rupture influence on 3D permeabilities

Axial: $k_{az,FL\ before\ failure}$ = 1185 mD
$k_{az,FL\ after\ failure}$ = 1560 mD

Radial: $k_{rx\ before\ failure}$ = 2139 mD
$k_{rx\ after\ failure}$ = 631 mD

Sulem et Ouffroukh (2005) *Rock Mech. and rock eng.*

Experimental results : intermediate permeability limestone (Estaillades)

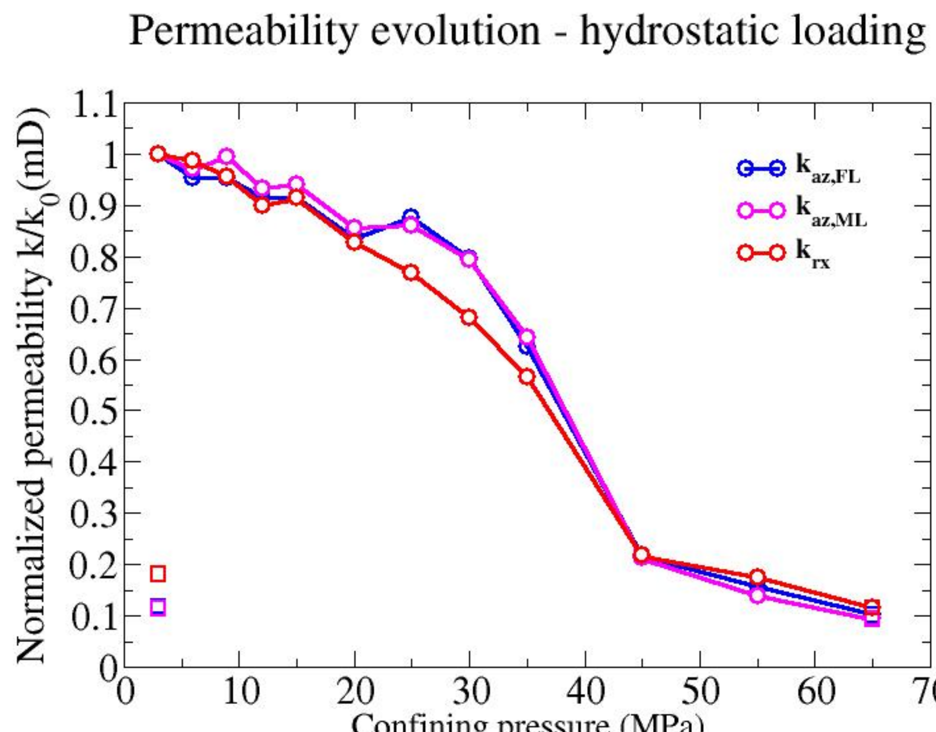


Homogeneous Pore Collapse
P* = 30 MPa

$k_{0az,FL}$ = 152 mD
$k_{0az,ML}$ = 162 mD
k_{0ry} = 70 mD

P*

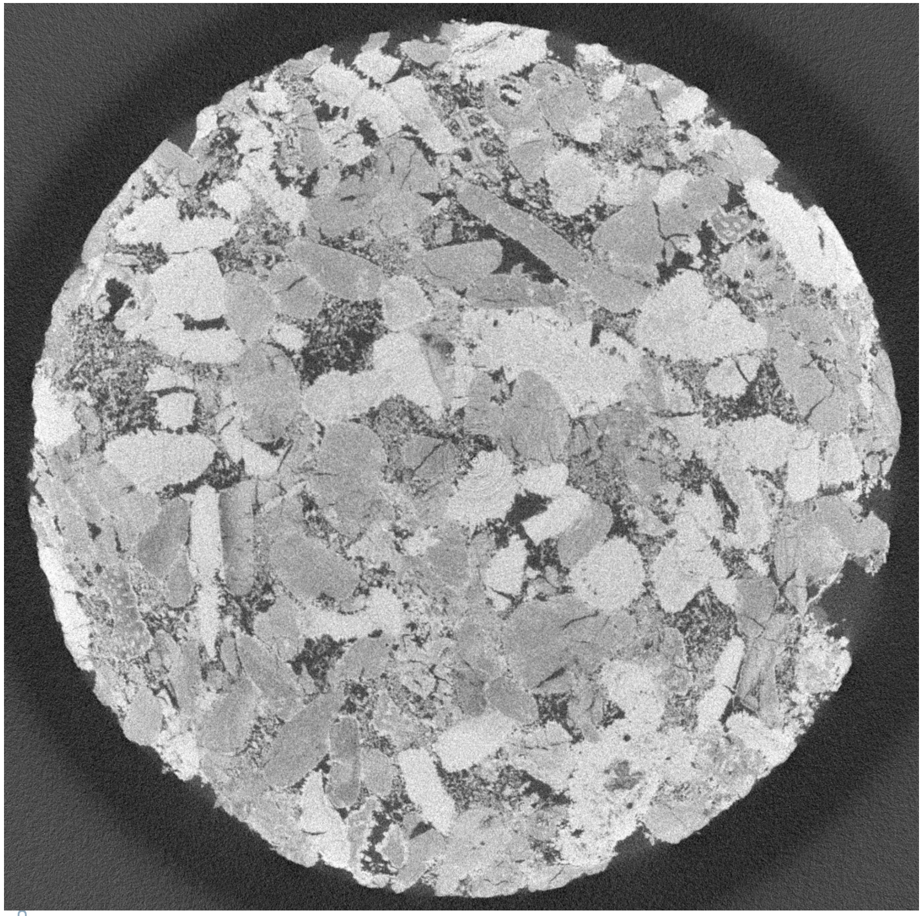
$k_{0az,FL}$ = 20 mD
$k_{0az,ML}$ = 20 mD
k_{0ry} = 13 mD



Experimental results : Intermediate permeability limestone (Estaillades)

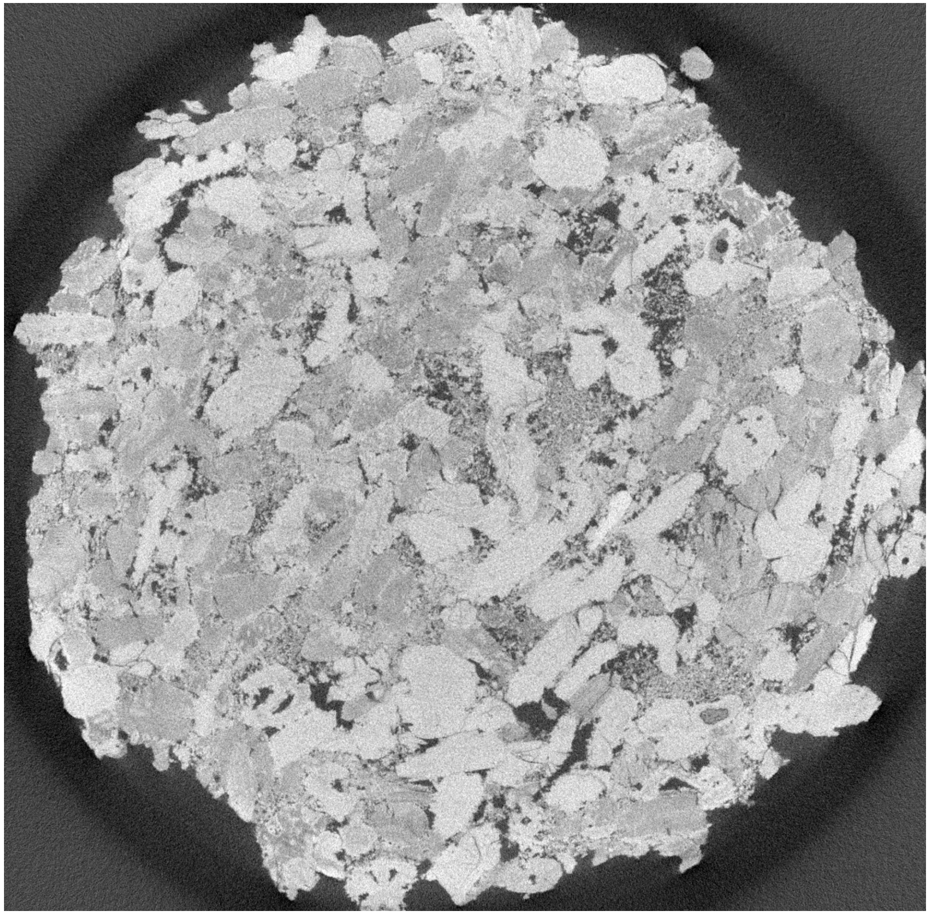
High Resolution Micro-Scanner Slides (3 µm resolution)

BEFORE LOADING



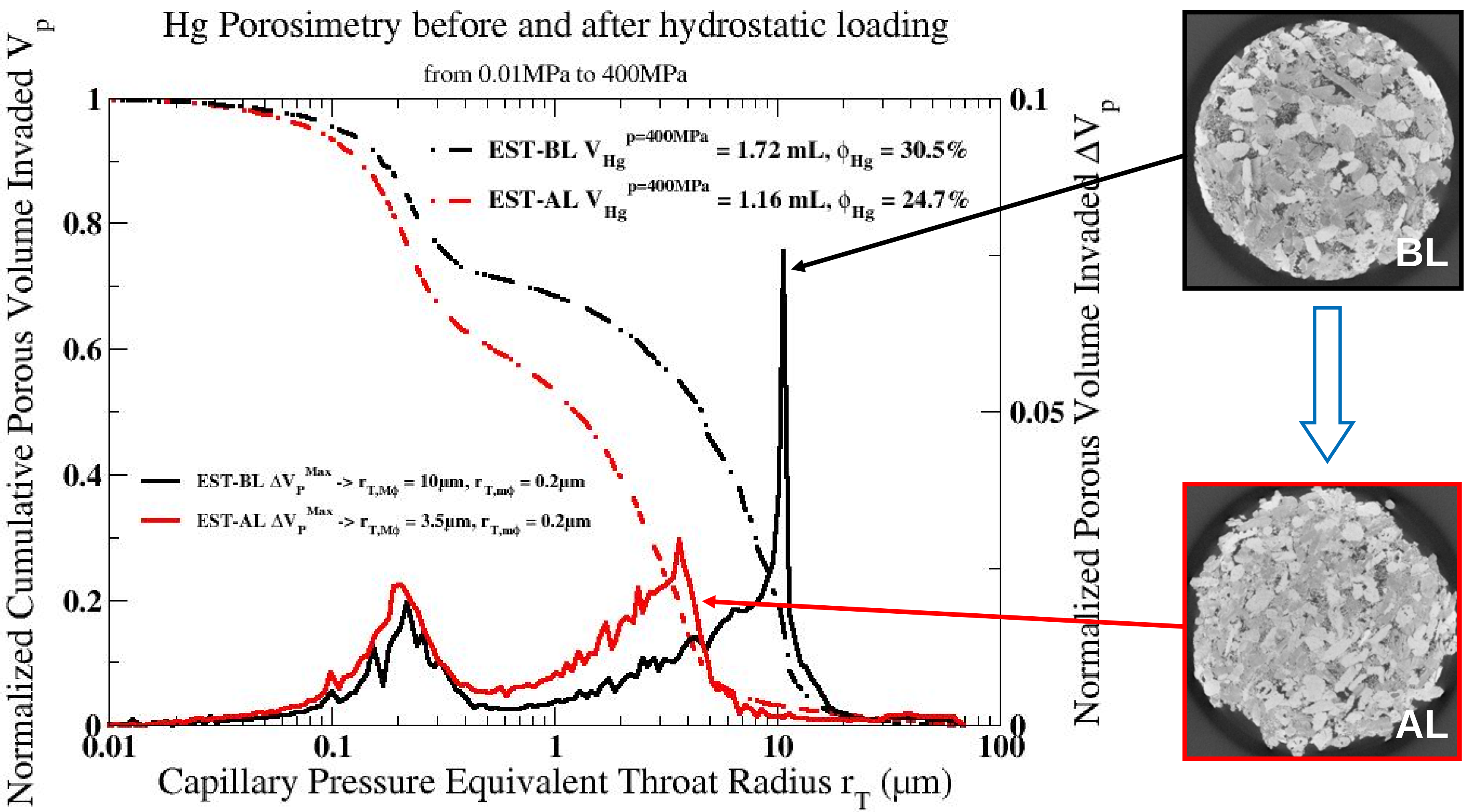
5 mm

AFTER LOADING



5 mm

Experimental results : Intermediate permeability limestone (Estaillades)



CONCLUSIONS #1

- Simultaneous radial and axial permeability measurements are feasible.
- Classical axial permeability measurements may be affected by end effects.
- The pressure dependency of permeabilities is well captured.

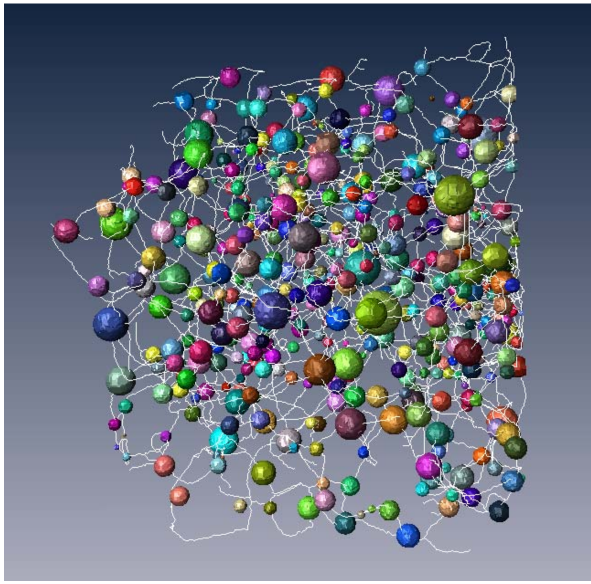
ON GOING EXPERIMENTAL WORK :

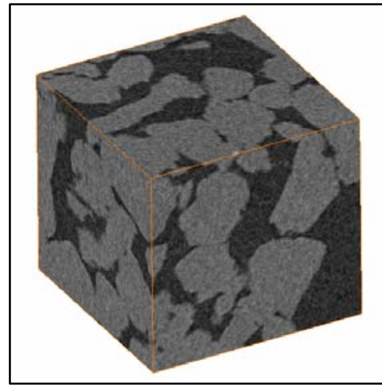
- *Investigation of the influence of strains localization on flow properties (In-situ Observations)*
- *Focus on stress paths more representative of reservoir conditions.*

PORE SCALE MECHANISMS MODELISATION

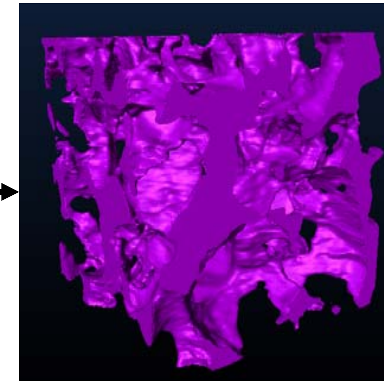
Modelisation of pore-scale mechanisms

Equivalent Pore Network extraction* :

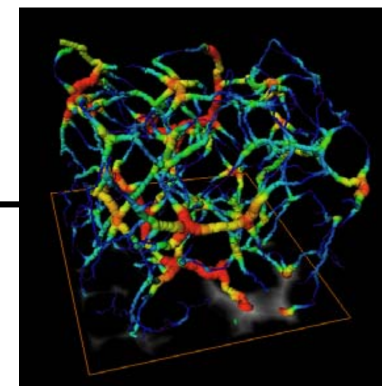




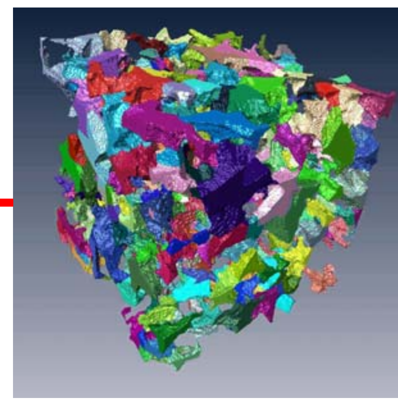
Microtomography 3D Reconstruction



Porosity threshold



Pore Network Skeletonization
local minimum radius



Individual Pore Indexation

Pores: Equivalent Volume spheres
Throats: Cylindrical channels

Output data:

Throats dimension: L_T, r_T & AR
Equivalent pores volumes: ϕ
Network connectivity

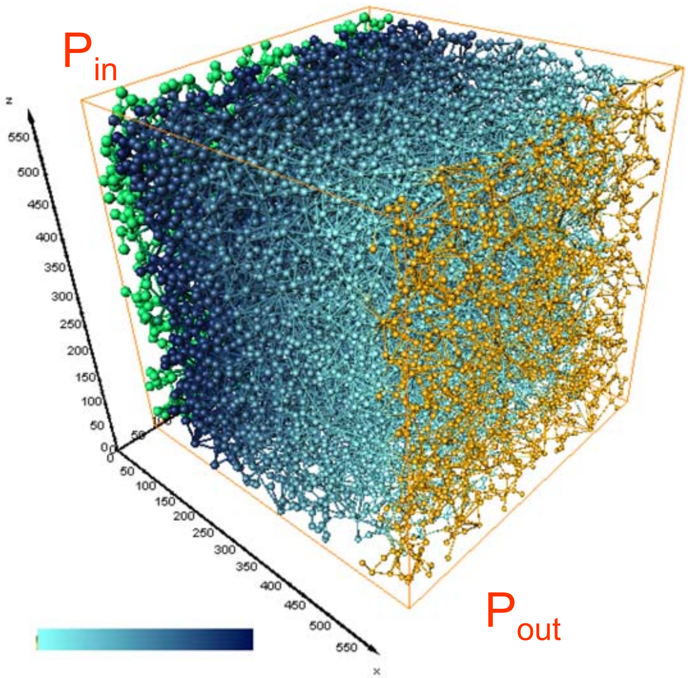
* Youssef et al. (2007) *SCA*

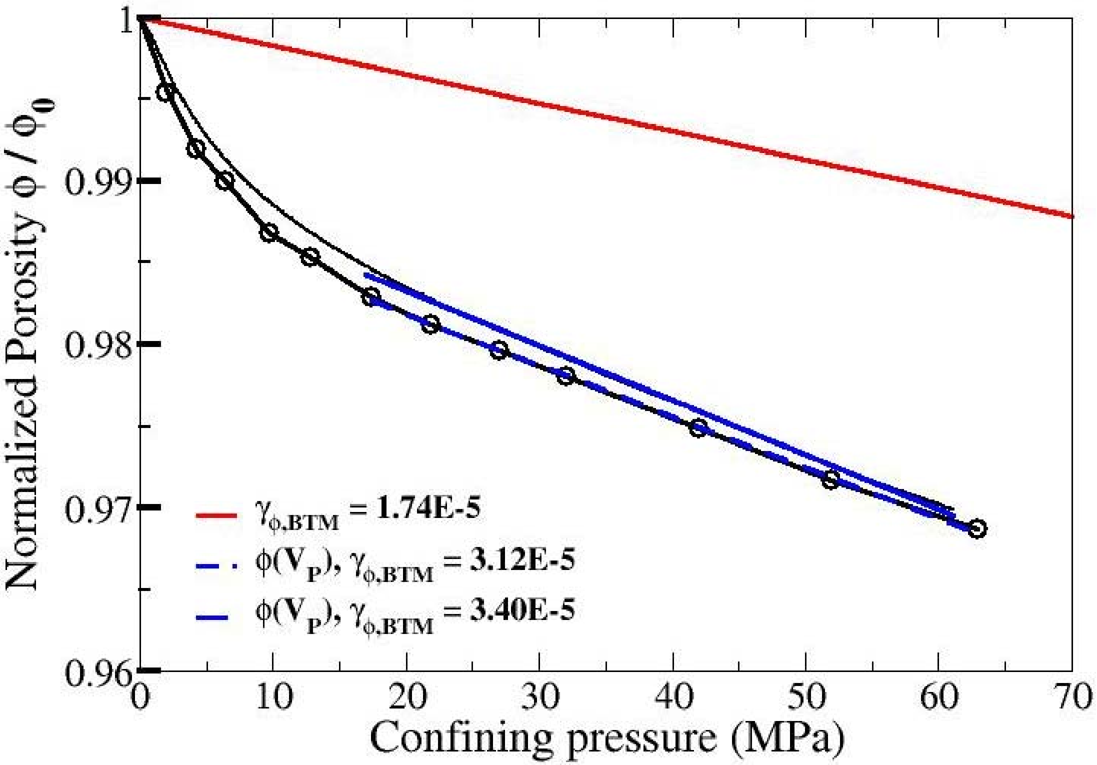
Modelisation of pore-scale mechanisms : Fluid flows and compaction coupling

Transport properties simulation	Network compaction implementation
Individual channel conductance : $$g = \frac{\pi}{8}\frac{r^4}{L}$$ **Problem formulation :** In the throat between pores i and j $$q_{ij} = g_{ij}(P_i - P_j)$$ In the Pores : $$\sum_{i \to j} q_{ij} = 0$$ Matrix formulation : $$G \bullet \vec{P} = \vec{S}$$ → **Resolution of network effective hydraulic conductivity**	Spherical Pores: $$r_p \cong r_{p,0}(1-\gamma_p(p-p_0))^*$$ $$\gamma_p = \frac{(1+\upsilon)}{2E}^{**}$$ Cylindrical Pore Throats: $$r_T \cong r_{T,0}(1-\gamma_T(p-p_0))^*$$ $$\gamma_T = \frac{(1+\upsilon^2)}{E}^{**}$$ l_T pressure dependency neglected $$g_T(P) \longrightarrow G(P) \longrightarrow k(P)$$ * Bernabé et al. (1982) *Mech. of Materials.* ; Bernabé et al. (1995) *JGR* ** Jaeger et Cook (1976) Fundamental of Rock Mechanics.

Modelisation of pore-scale mechanisms : Bentheimer Sandstone Example

Extracted equivalent pore network
Volume = 500x500x500 x6μm

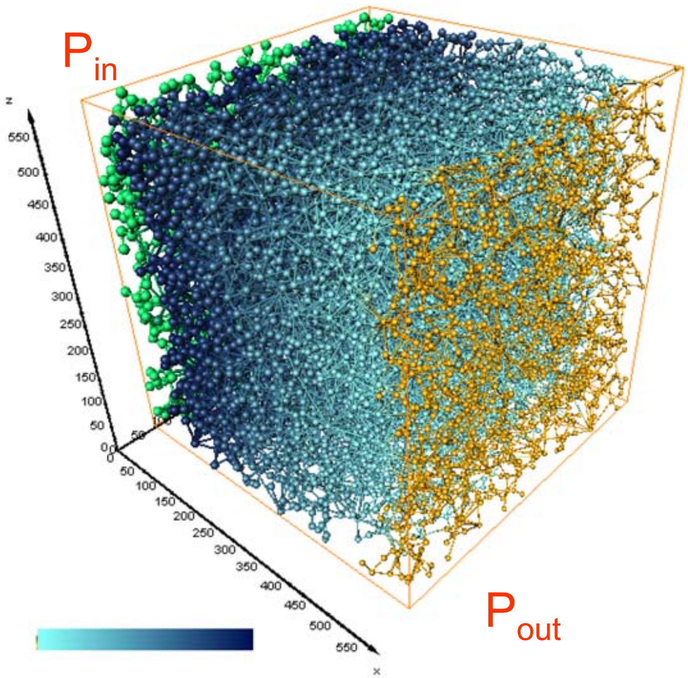


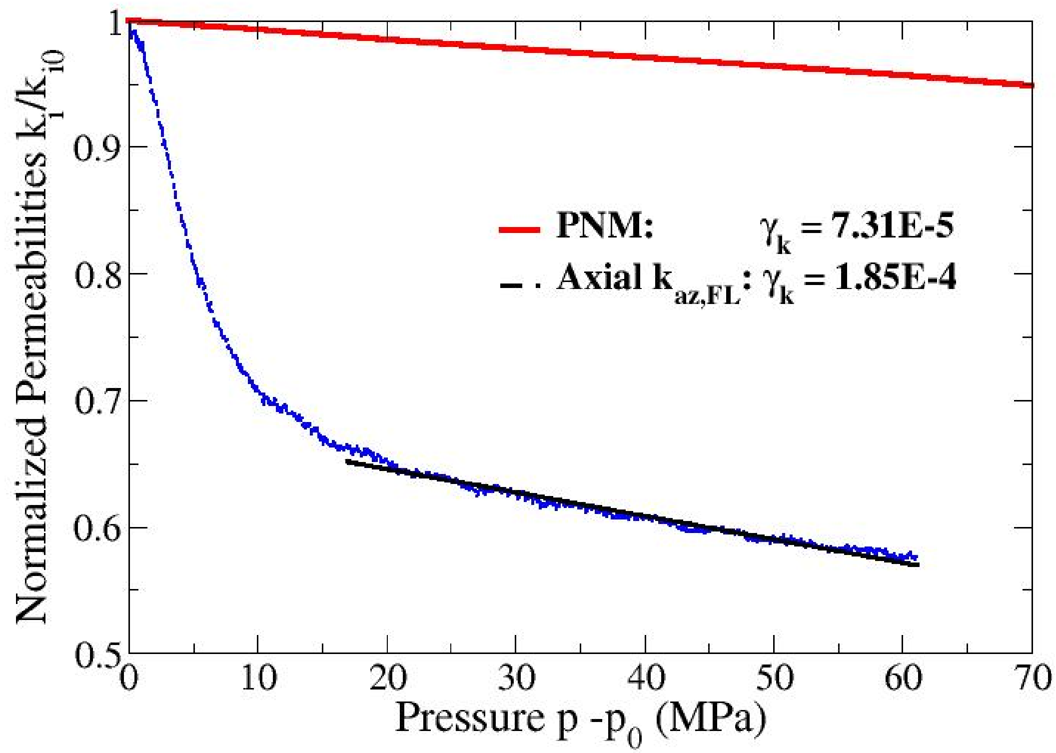


$$\phi_{exp} = 24.5\% \Longleftrightarrow \phi_{\mu CT} = 24.4\%$$

Modelisation of pore-scale mechanisms : Bentheimer Sandstone Example

Extracted equivalent pore network
Volume = 500x500x500 x6μm





$$k_{\exp} = 3000mD$$

$$k_{\mu CT} = 847mD$$

$$A_{k,\mu CT} < 10\%$$

Discrepancy lies to the definition of r_T
(minimum local pore throat radius)

$$g_h = \frac{\pi}{8}\frac{r_T^{\ 4}}{L}$$

Innovation Energy Environment

CONCLUSIONS #2 :
MICRO-TOMOGRAPHY CONTRIBUTION

- **Simple pressure dependency model can be applied on the equivalent pore network.**

ON GOING NUMERICAL WORK :

- ***Alternative description of throats dimensions***
- ***Investigation of the anisotropic distribution of the channels***

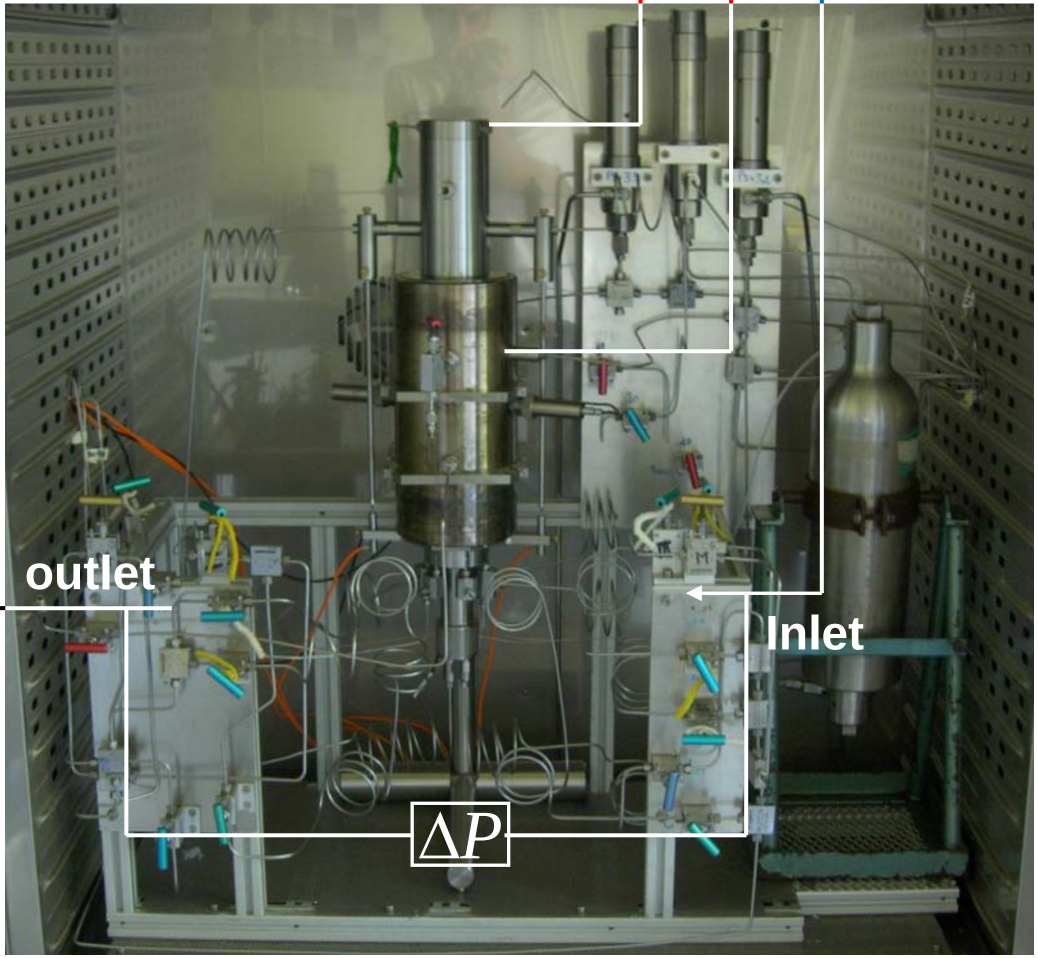
- ***FEM simulation of the coupled effects of deforming matrix and fluid flows (TRUE GEOMETRY OF THE POROSITY)***

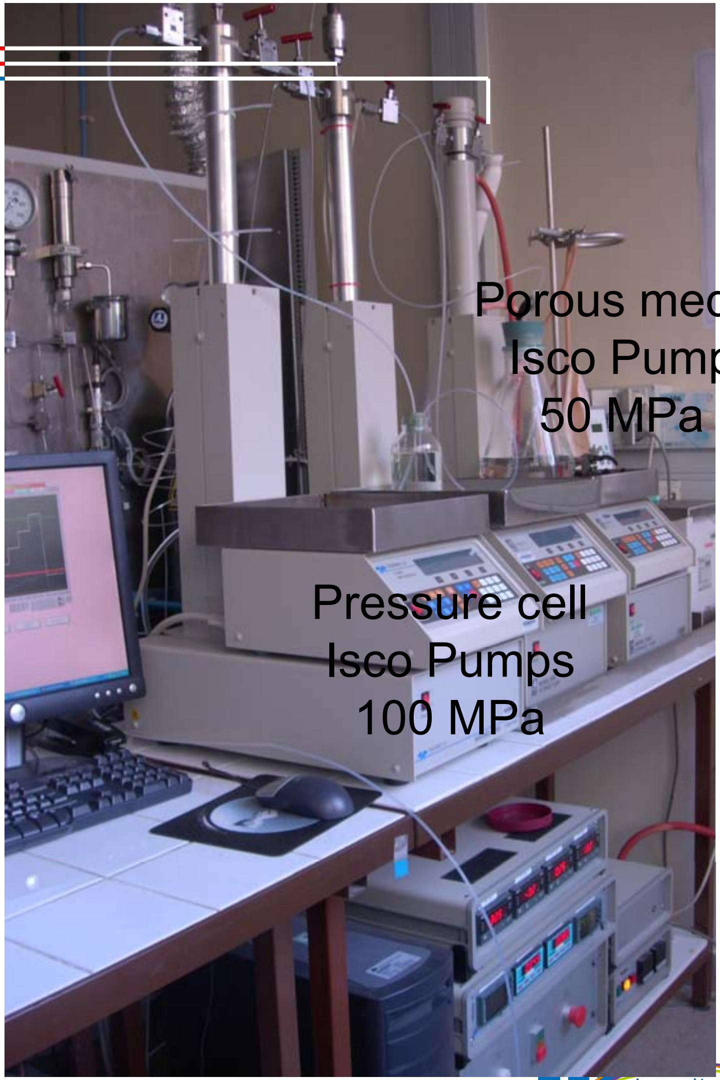
THANKS FOR YOUR ATTENTION

New Experimental Set-up :
Triaxial cell specially designed to directional permeabilities measurements

Pmax = 69 MPa

Max Using Temperature = 130°

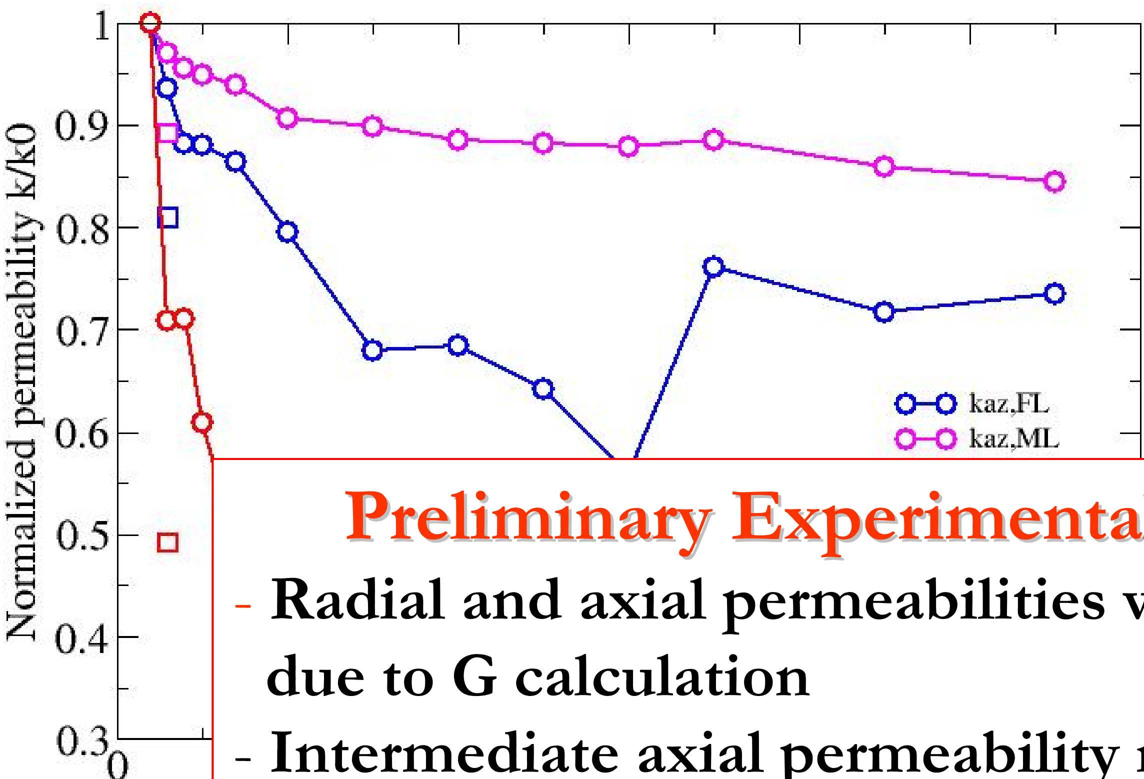


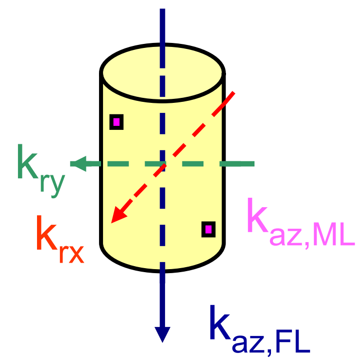


Experimental results : Low permeability sandstone (Fontainebleau)

Sample 2 : $\phi = 8\%$

Directional permeability evolution SAMPLE 2





Preliminary Experimental Conclusions :

- **Radial and axial permeabilities values differences due to G calculation**
- **Intermediate axial permeability measurements looks more consistent than classical measurements**