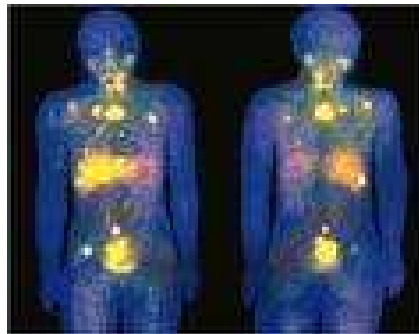


# Comportement thermo-hydromécanique des argiles en vue du stockage des déchets radioactifs

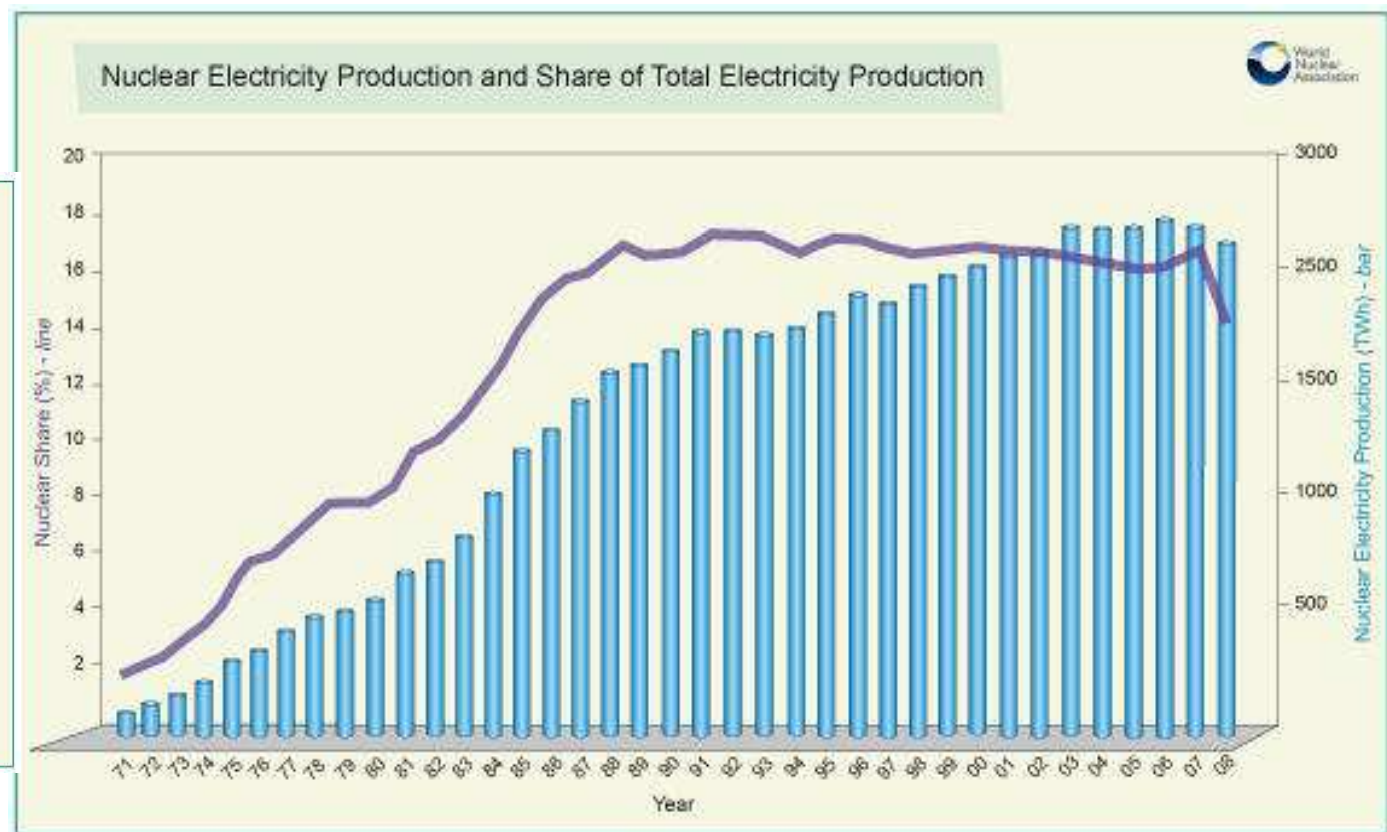
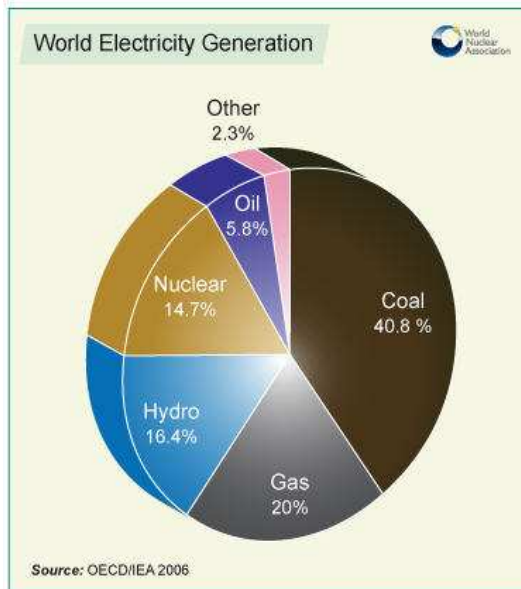
Frédéric Collin, Université de Liège

- 
- **Introduction**
  - **Nuclear waste disposal**
  - **ATLAS experiment - THM modelling**
  - **GED gallery - HM modelling**
  - **Conclusions**

- Electricity production
- Nuclear medicine
- Scientific researches
- Dating (Carbon 14)
- Military purposes
- ...



The **nuclear electricity** corresponds to 14.7 % of the total amount of the world electricity generation in 2008.

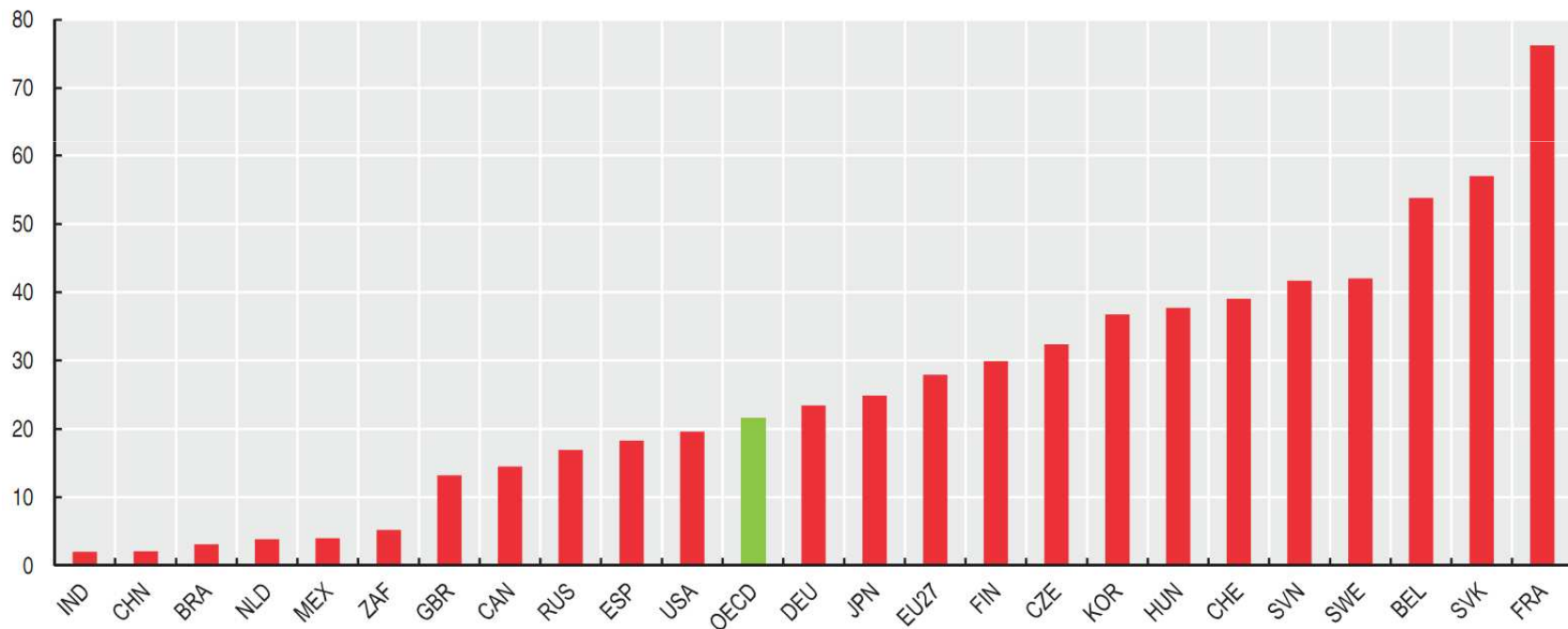



However, there are some **disparities** between the countries !

(21% of the total amount in OECD countries, which represent 83% of the world production).

### Production d'électricité nucléaire

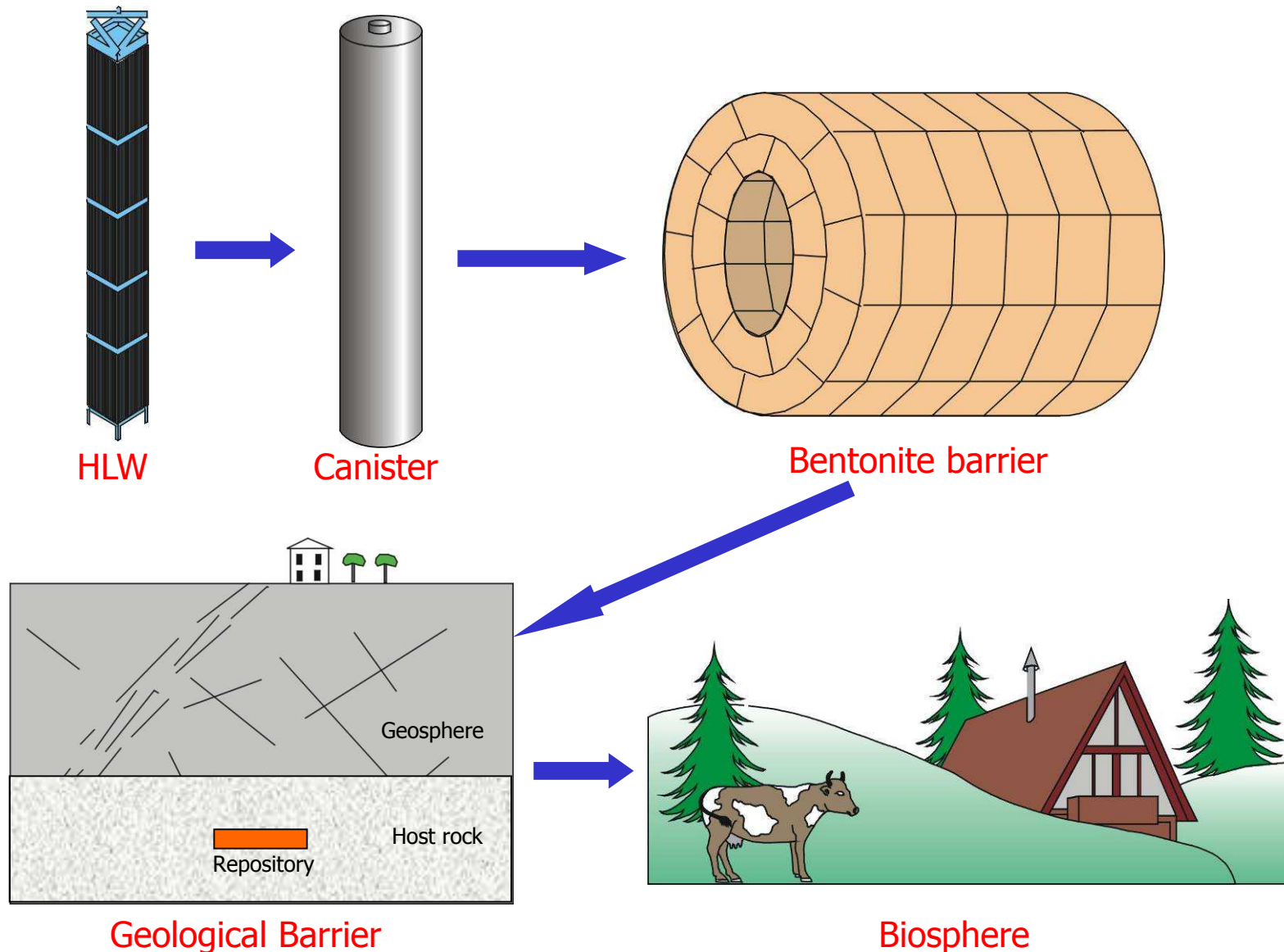
*En pourcentage de la production totale d'électricité, 2008*



StatLink  <http://dx.doi.org/10.1787/820210813782>

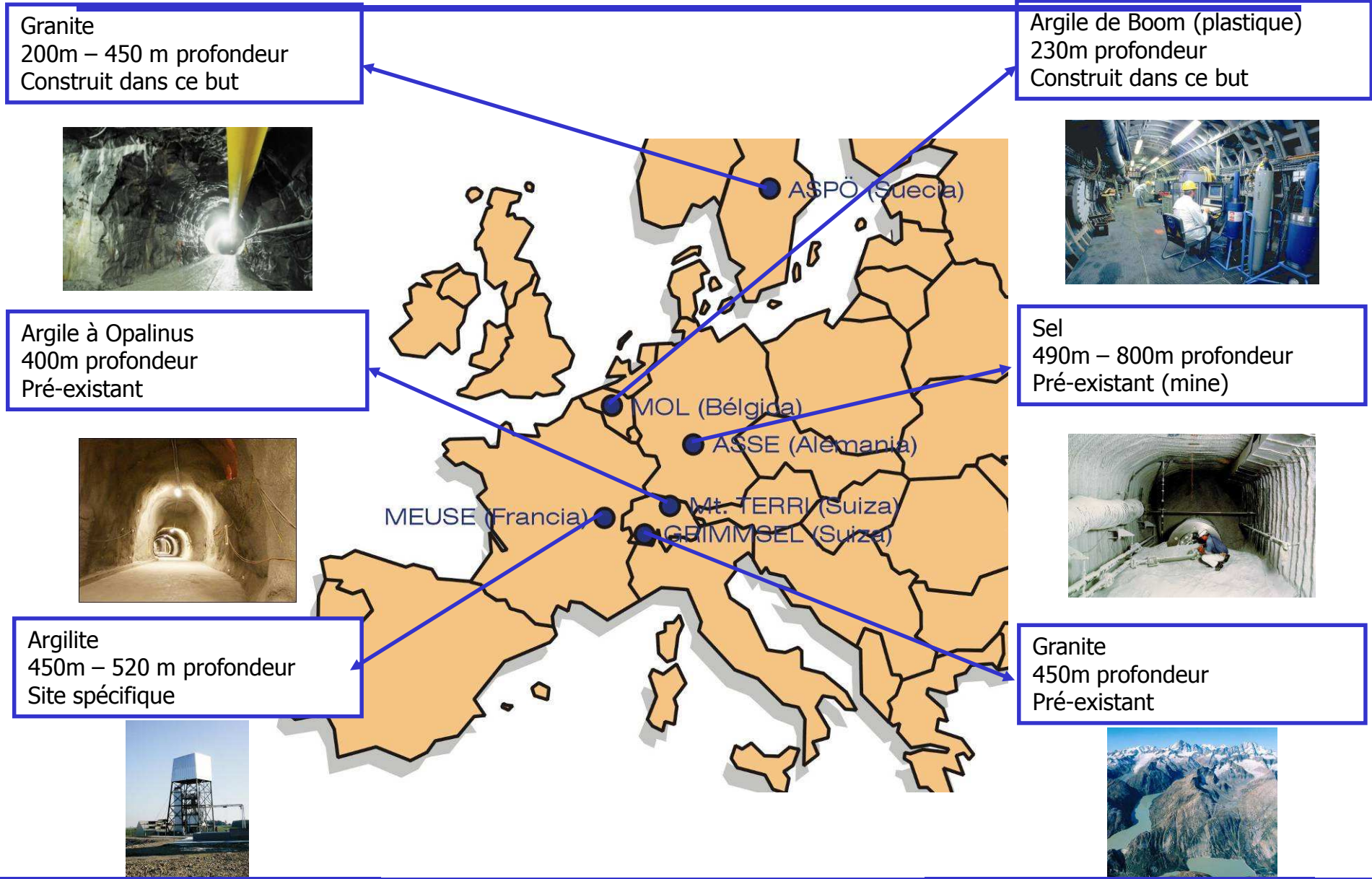
Types of nuclear wastes

	Short life (< 30 ans)	Long life (> 30 ans)
Low activity	<b>Waste A</b>  90% Volume 1% Radioactivity  70 500 m <sup>3</sup> in 2070 in Belgium	
Medium activity		<b>Waste B</b> 8% Volume 4% Radioactivity  8900 m <sup>3</sup> in 2070 in Belgium
High activity		<b>Waste C</b> 2% Volume 95% Radioactivity  3000 m <sup>3</sup> in 2070 in Belgium



- 
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  - **Conclusions**





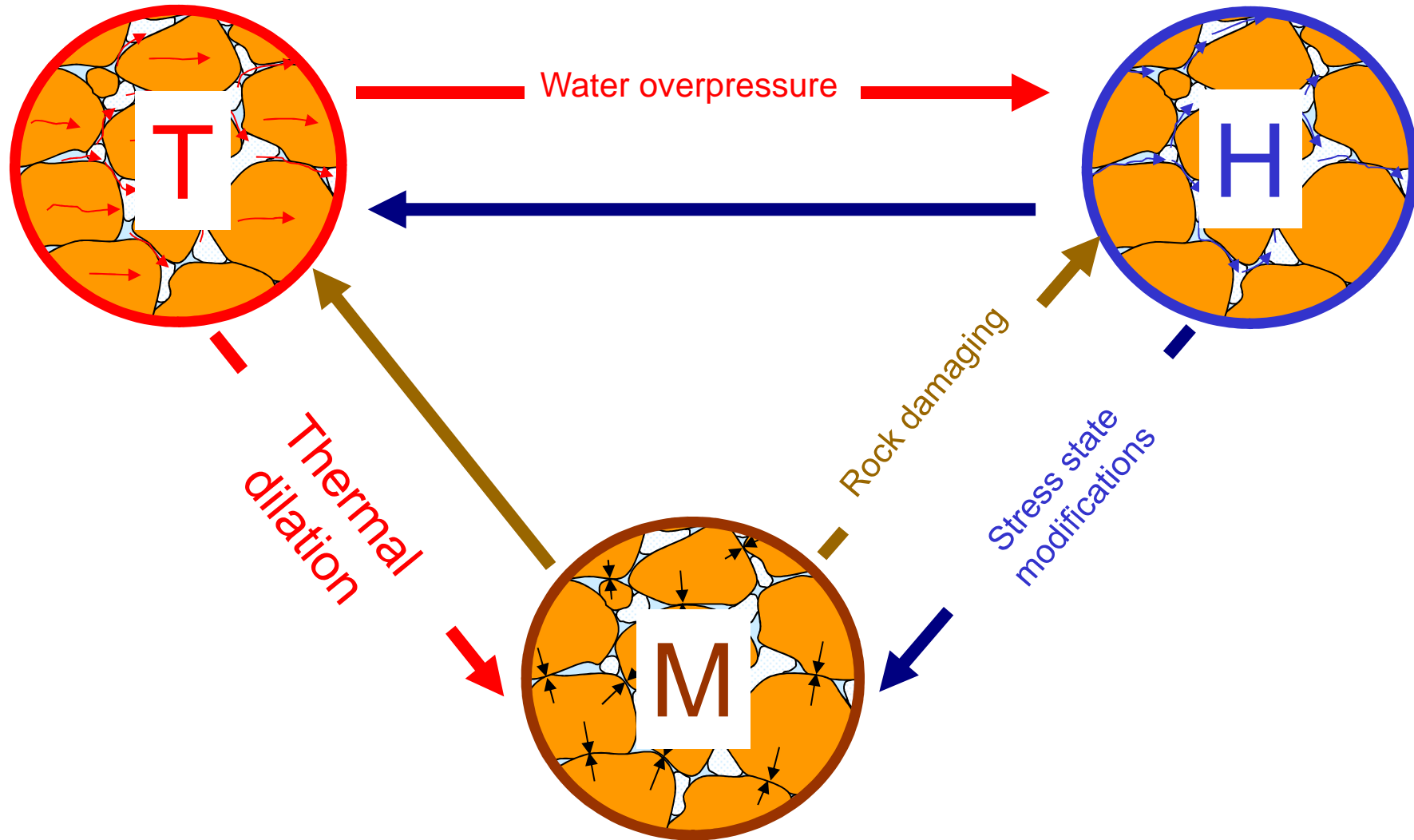
- Analysis of the multi-physical loadings
  - Gallery excavation → *Mechanical*
  - Water flow → *Flow*
  - Gas movement (corrosion) → *Flow*
  - Heating – Cooling → *Thermal*
  - Tightening of the gallery → *Mechanical, flow*
  - ...

→ Multi-physical couplings



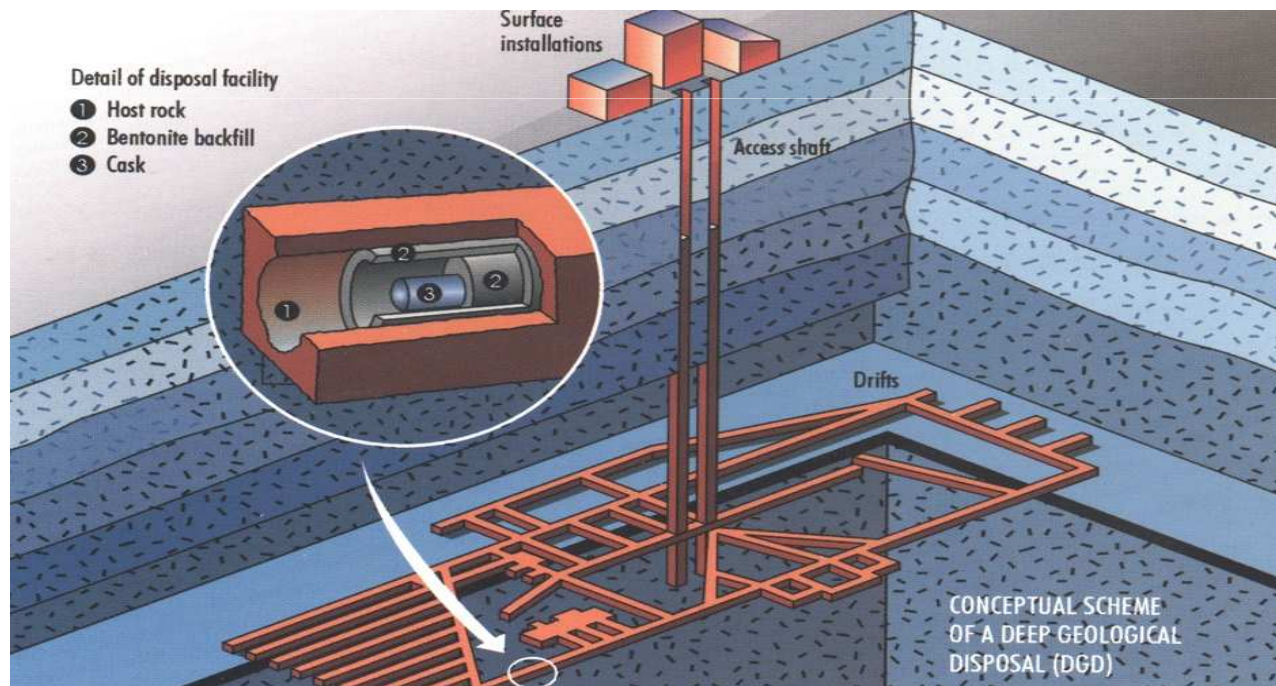
Heat transfer

Water and gas flow



Mechanics

- Understand the multi-physical processes
  - Laboratory experiment
  - In situ experiment
  - Modelling → Prediction of the long term behaviour

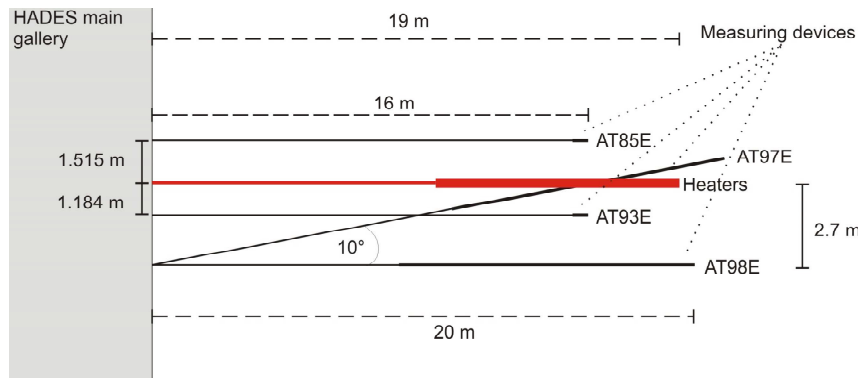


- 
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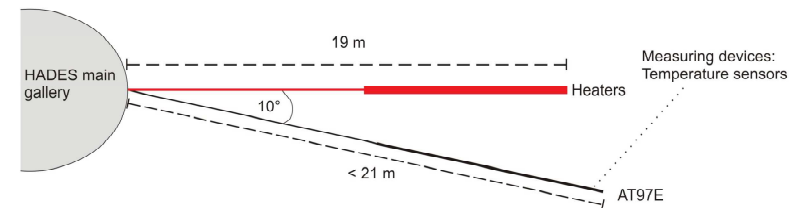
- ❑ Modélisation de l'expérience in-situ *ATLAS III*:
  - Caractériser le comportement thermo-hydro-mécanique de l'Argile de Boom (caractérisation des propriétés thermiques...)

Expérience: 1 forage principal (résistances chauffantes)

4 forages annexes (instrumentation: piézomètres, thermo-couples...)



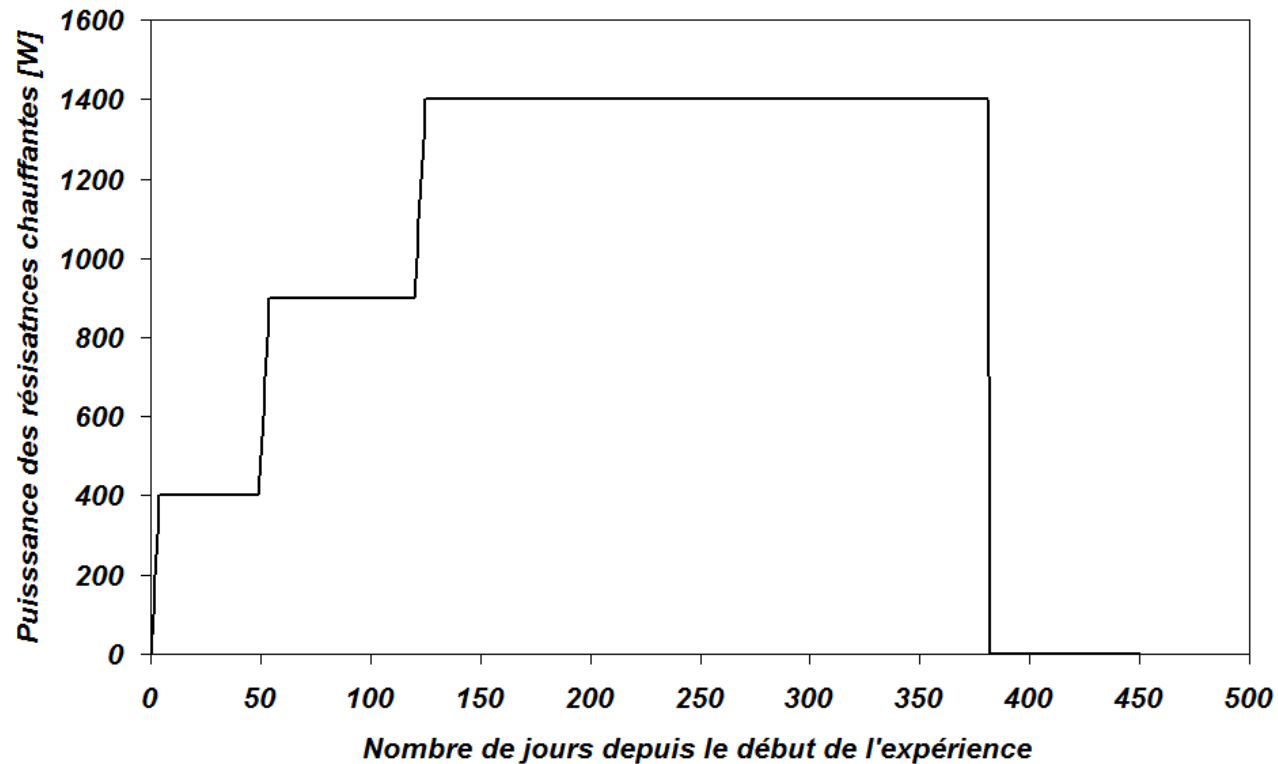
***Vue dans un plan horizontal***



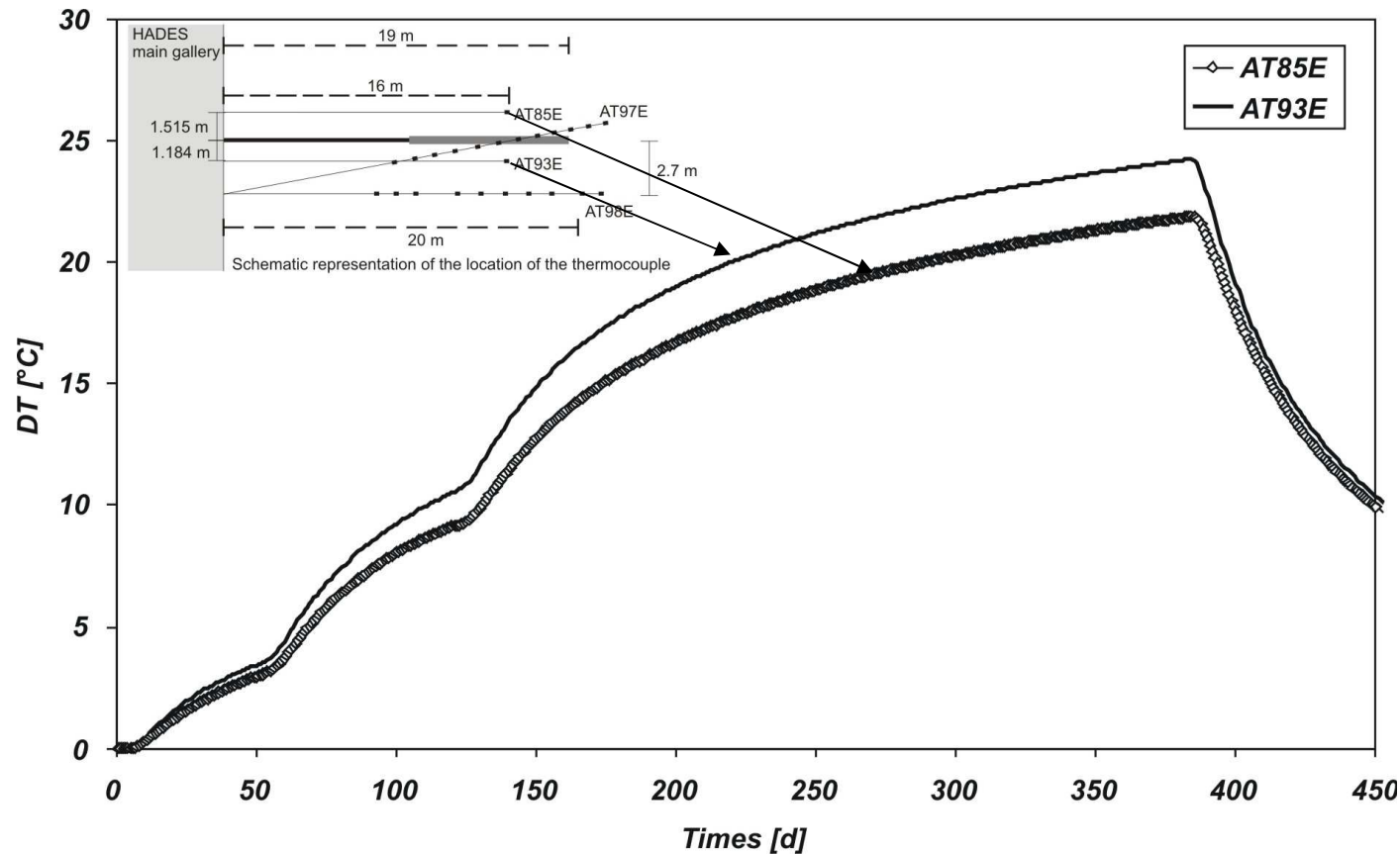
***Vue dans un plan vertical***

- ❑ Expérience hors de la zone d'influence (EDZ) de la galerie principale

- ❑ Déroulement de l'expérience: chauffage en trois étapes suivi de période de stabilisation



Expérience ATLAS III: résultats expérimentaux, évolution de la température

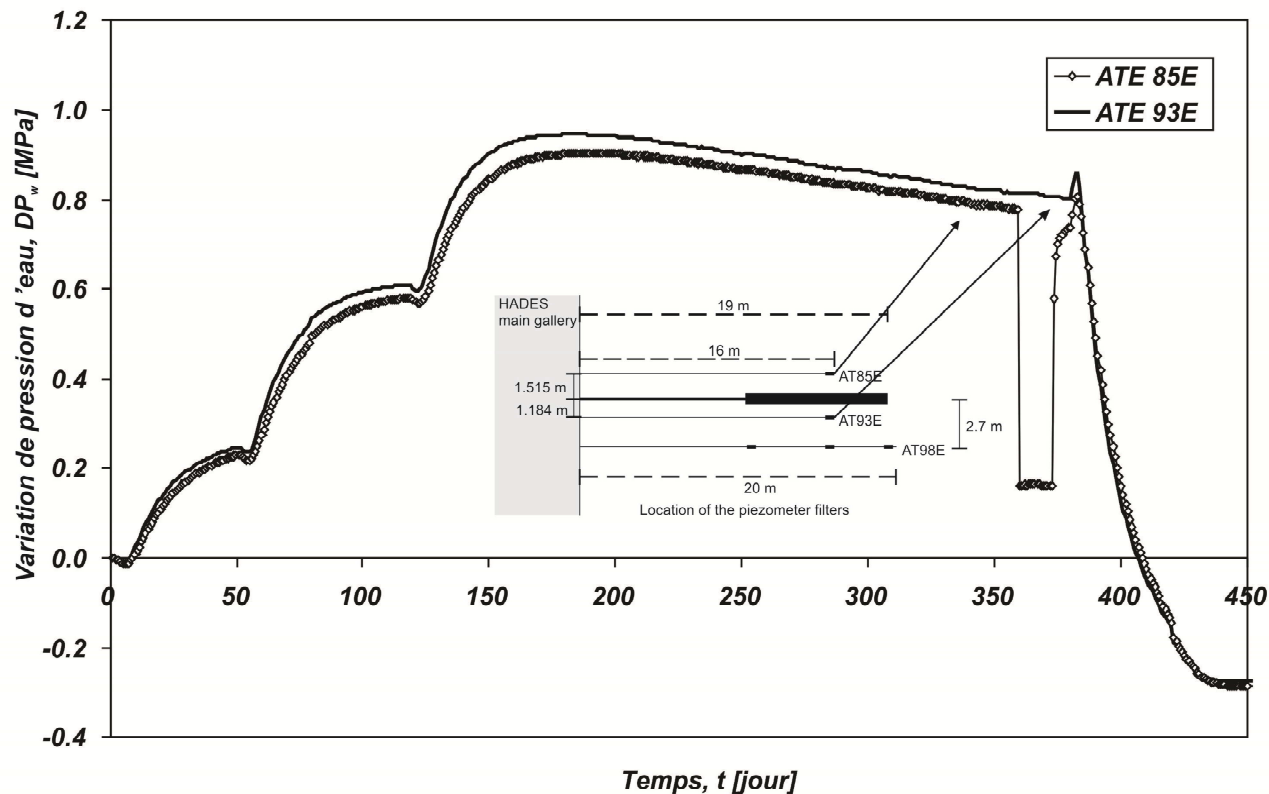


Evolution de la température (AT85E/AT93E)



❑ Expérience *ATLAS III*: résultats expérimentaux

Evolution de la pression d'eau aux capteurs AT85E et AT93E



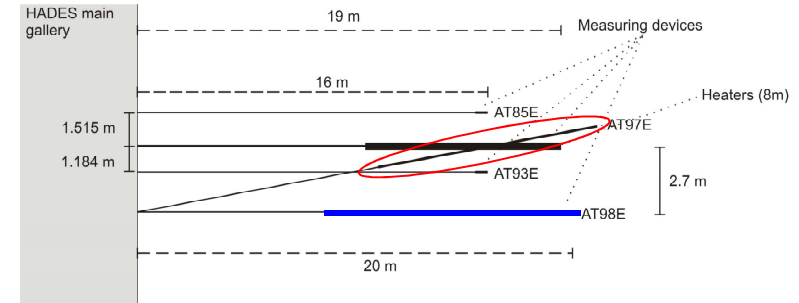
Modélisations réalisées:

- 2D axisymétrique: Modèle élastique linéaire avec thermo-élasticité
- 3D: Prise en compte de l'anisotropie (mécanique, hydraulique, thermique)  
Modèle élastique transversalement anisotrope avec thermo-élasticité

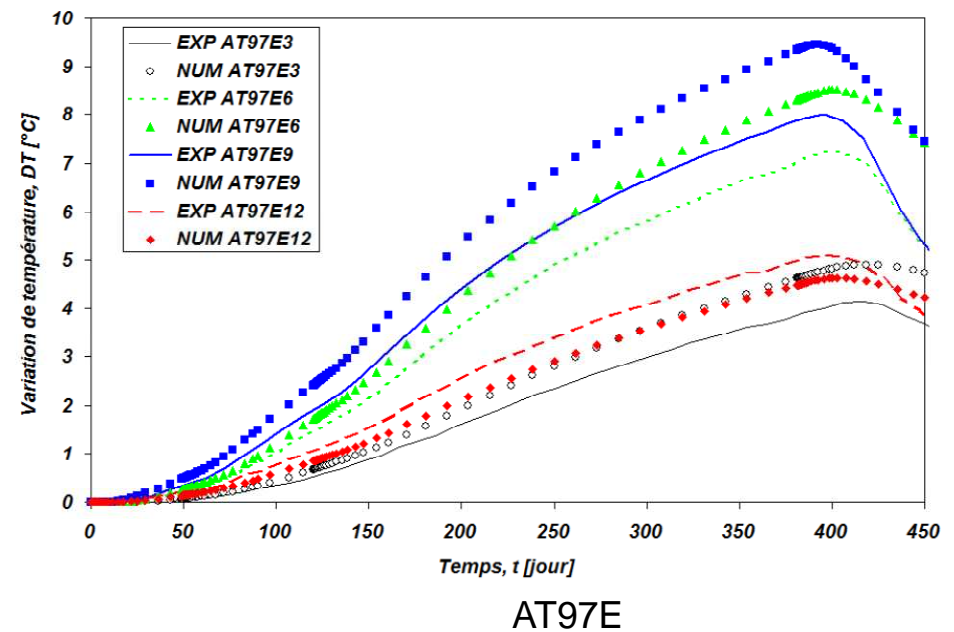
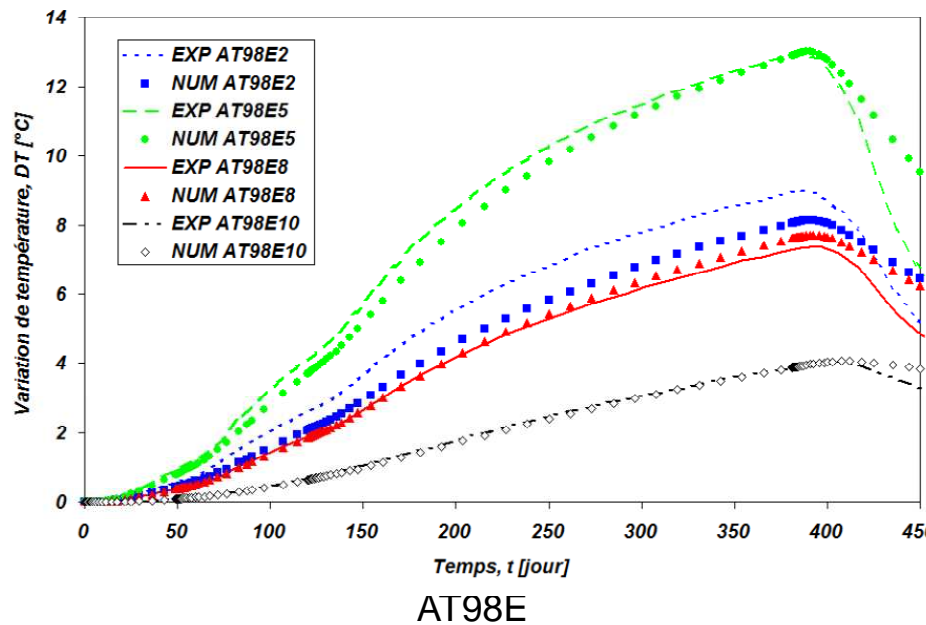
Pq des modèles élastiques linéaires?

- Rayon du forage principal (0.095m) → hypothèse zone plastique
- Position des points de mesures à plus de 1m du forage principal  
→ Zone non-affectée par le forage

❑ Résultats de la modélisation 2D

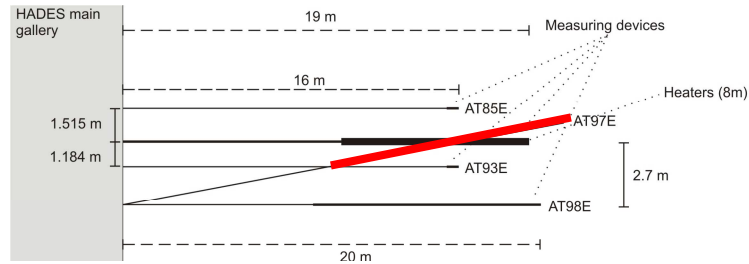


Comparaison entre les résultats num. et exp., évolution de la température

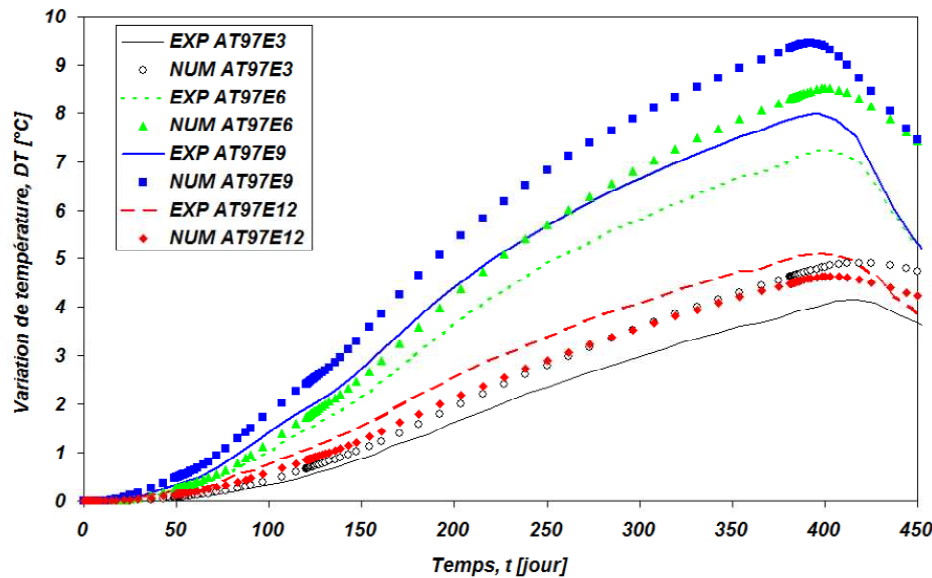


➔ Mauvaise prédiction des évolutions des températures pour AT97E

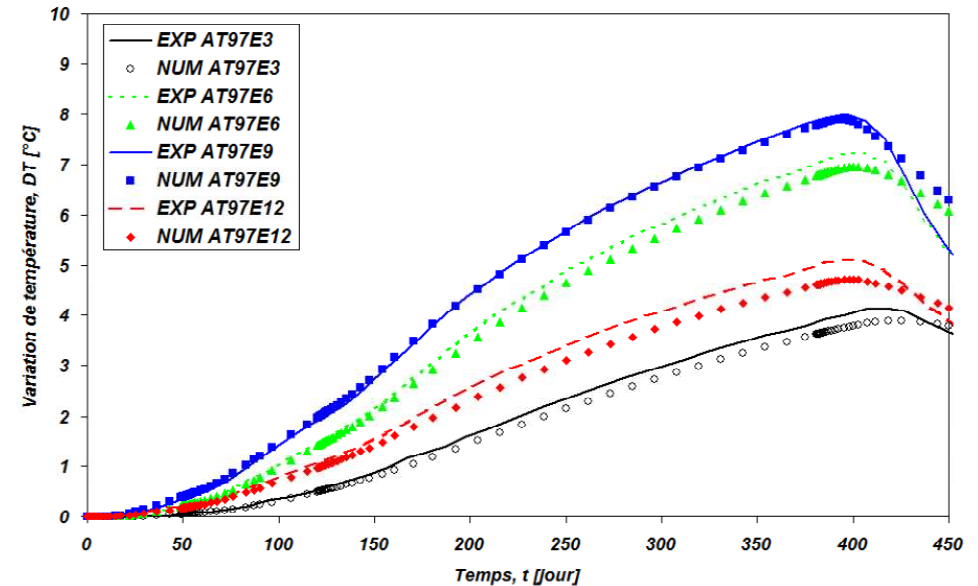
☐ Prise en compte de l'anisotropie de l'Argile de Boom → Modèle 3D



Comparaison entre les résultats num. et exp., évolution de la température (AT97E)



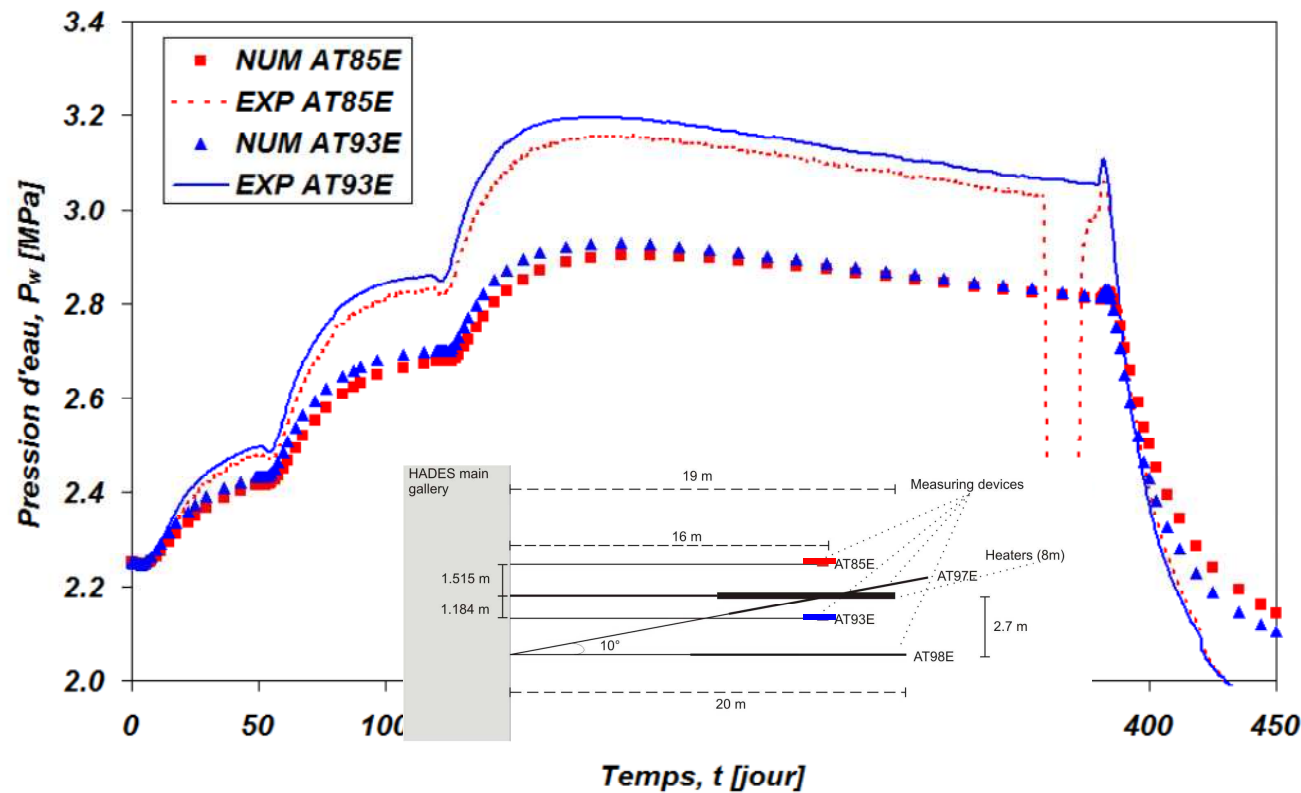
Modèle de conduction thermique isotrope



Modèle de conduction thermique anisotrope

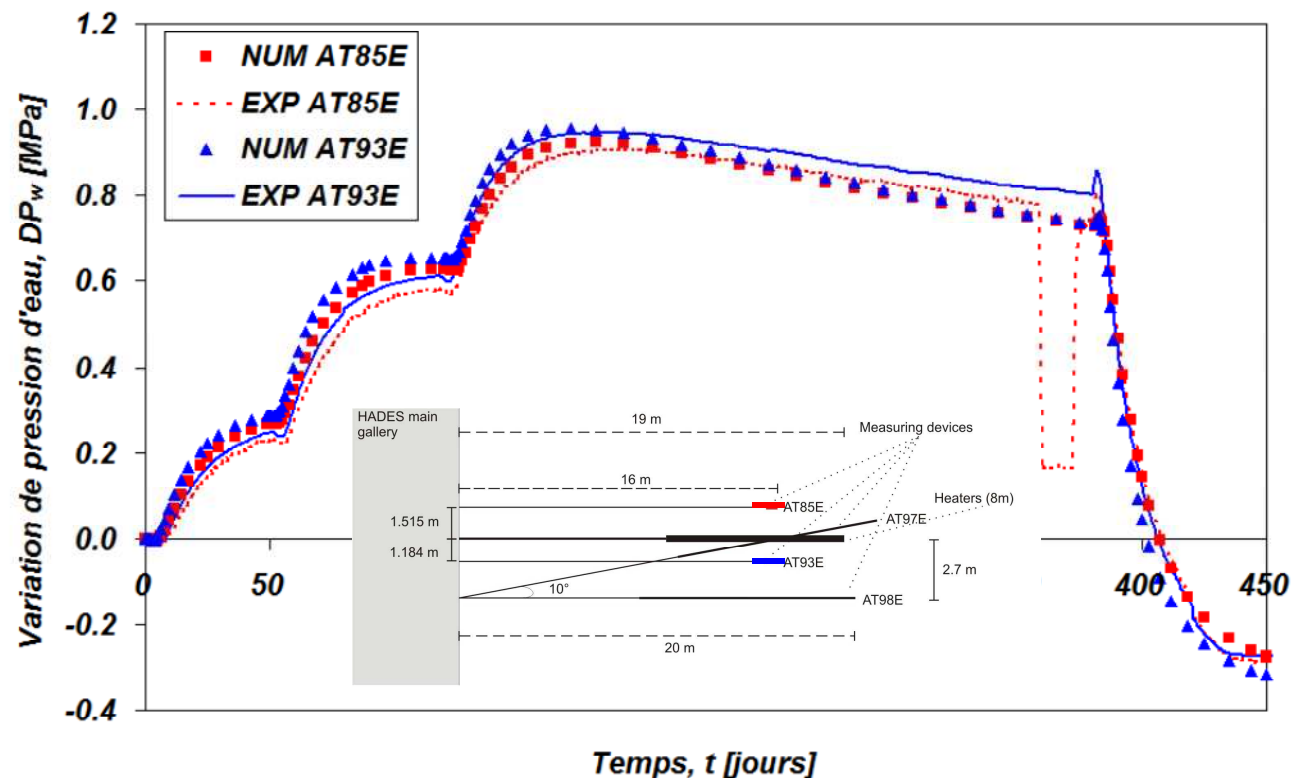
❑ Résultats modèle 3D complètement anisotrope:

Evaluation des pressions d'eau, comparaison entre les résultats num. et exp.



➔ Sous-estimation de l'évolution des pressions d'eau

- Contexte de prise en compte des petites déformations
  - ➔ Module de rigidité plus important (doublé)

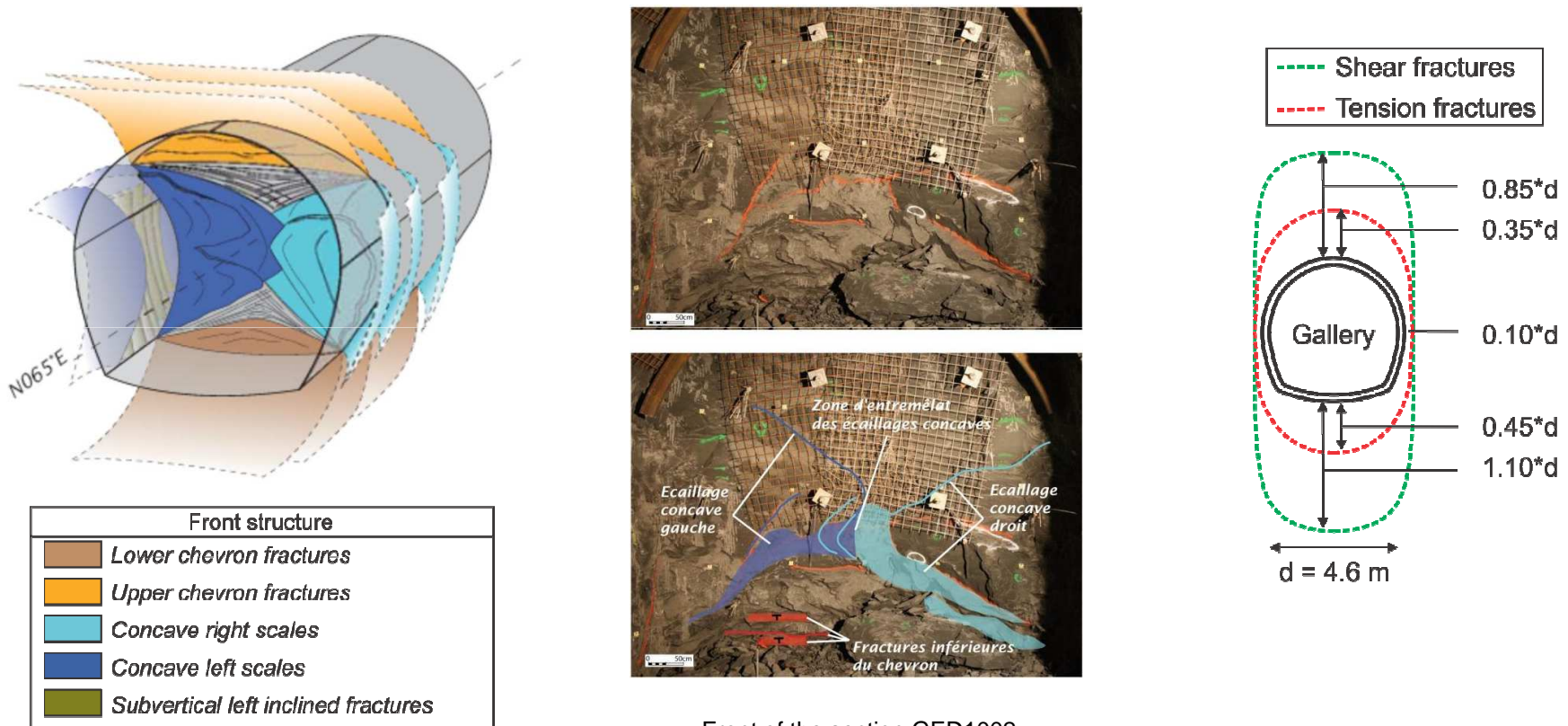


- ➔ Important: aspect anisotropie du matériau et caractéristiques élastiques

- 
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## In situ evidences :

Observations and measurements (ANDRA URL, GED Gallery, Cruchaudet *et al.* 2010a).



Front of the section GED1002

Major issues : prediction of the extension and fracturing structure.

- study - damaged zone development with shear strain localisation,
- influence of the gallery ventilation.



## Numerical modelling :

By symmetry: quarter of the gallery

HM modelling in 2D plane strain state.  
Gallery radius = 2.3 m.

- ▣ Constant pore water pressure ( $p_{w,0}$ )
- ← Constant total stress ( $\sigma_{y,0} / \sigma_{x,0}$ )
- ▶ Constrained displacement perpendicular to the boundary
- ▲ Constrained normal derivative of the radial displacement (Zervos *et al.* 2001)
- Impervious boundary

Anisotropy (Andra URL) :

→ hydraulic permeability anisotropy

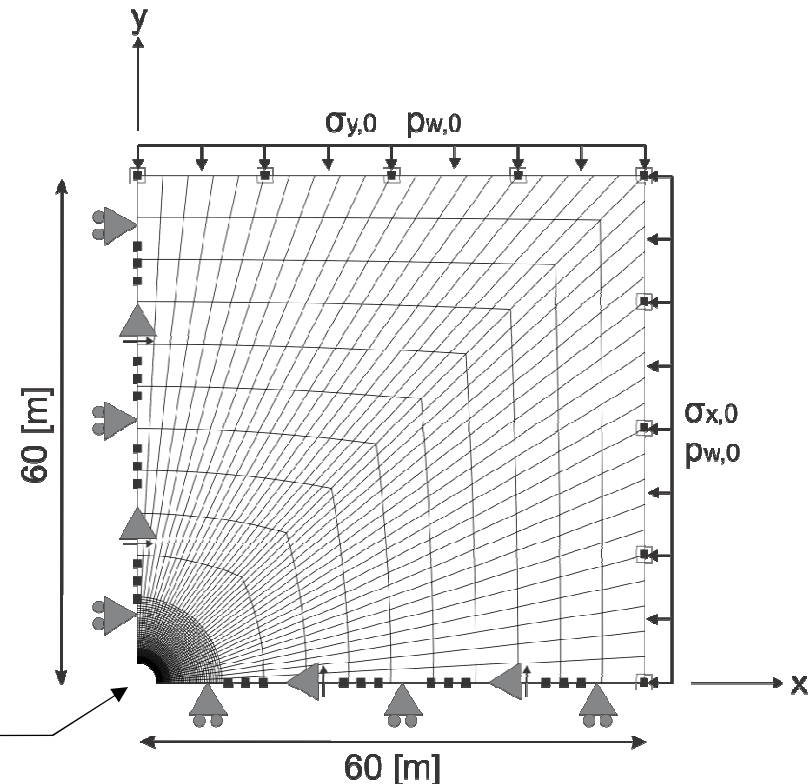
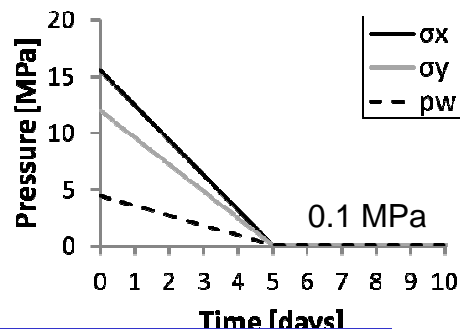
$$k_{hor/vert} = 4 \cdot 10^{-20} / 1.33 \cdot 10^{-20} [m^2]$$

→ initial anisotropic stress state

$$p_{w,0} = 4.5 [Mpa]$$

$$\sigma_{y,0} = \sigma_{z,0} = 12 [Mpa]$$

$$\sigma_{x,0} = 15.6 [MPa]$$

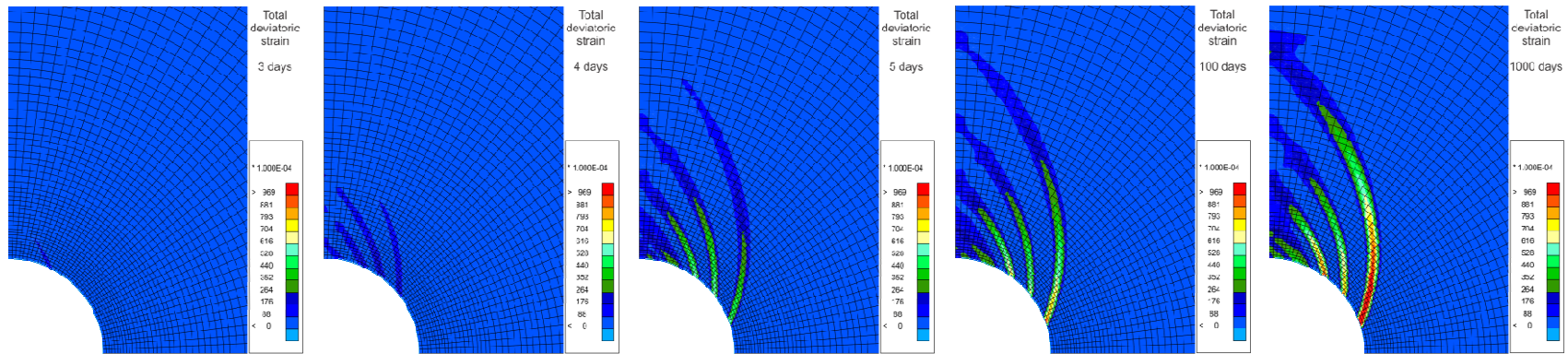


## Localisation zone :

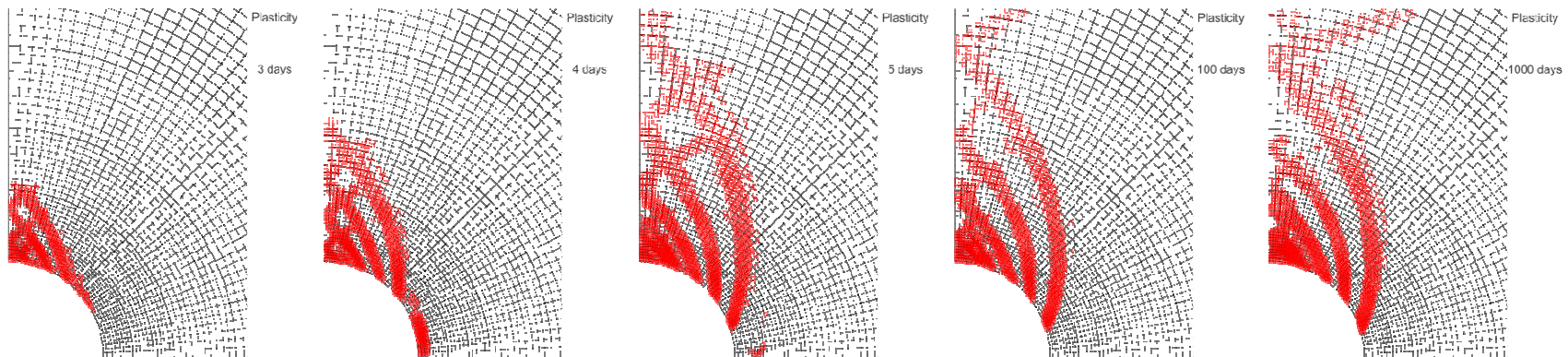
End of excavation



Total deviatoric strain



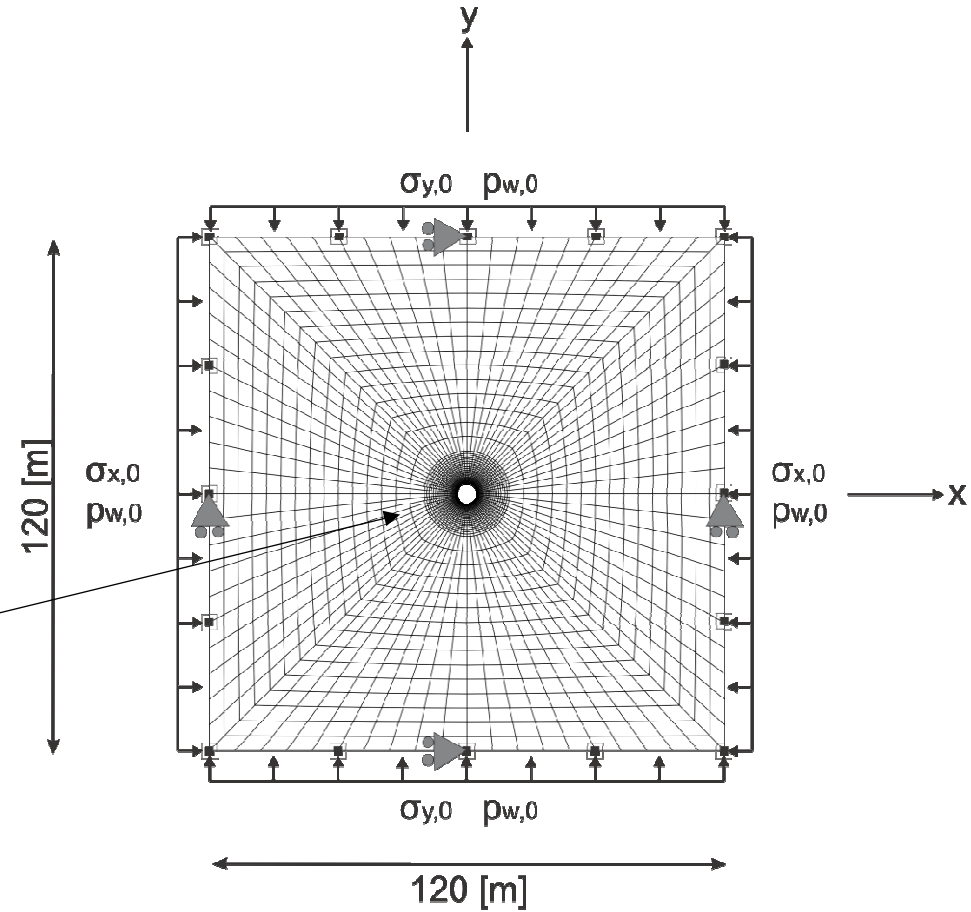
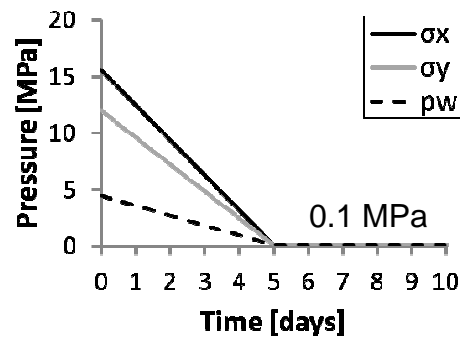
Plasticity



**Numerical modelling :**

Modelling of a full gallery to avoid symmetry.

- ▣ Constant pore water pressure ( $p_{w,0}$ )
- ← Constant total stress ( $\sigma_{y,0}$  /  $\sigma_{x,0}$ )
- ▶ Constrained displacement



## Localisation zone :

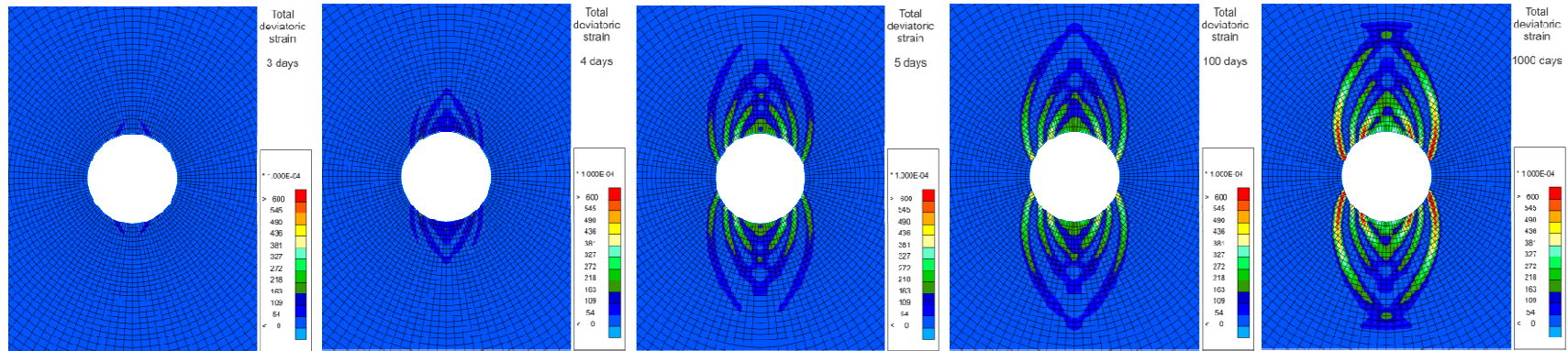
Anisotropic ( $\sigma$  and  $k$ )

End of excavation

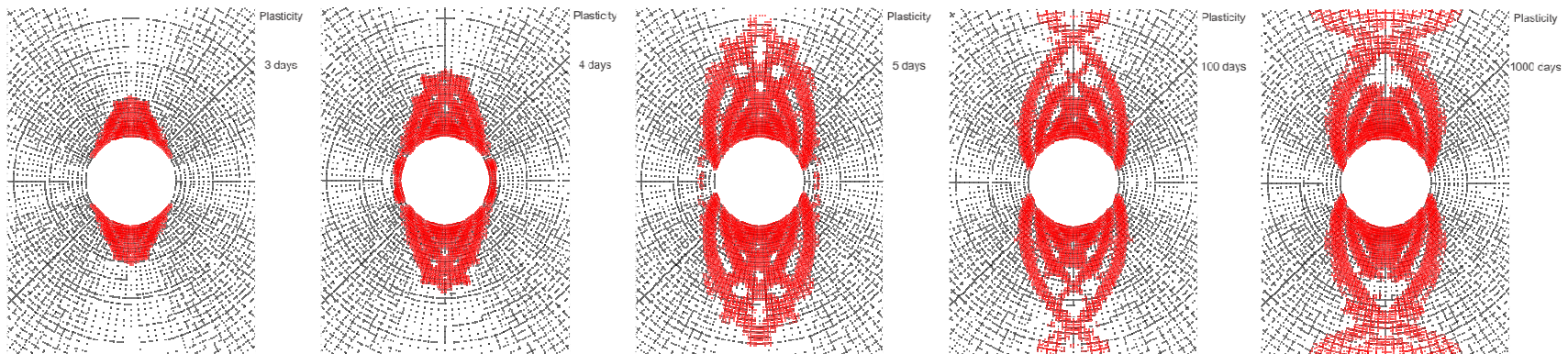


Same extension as with a quarter of a gallery

Total deviatoric strain



Plasticity



## Numerical modelling (LAGAMINE-ULg) :

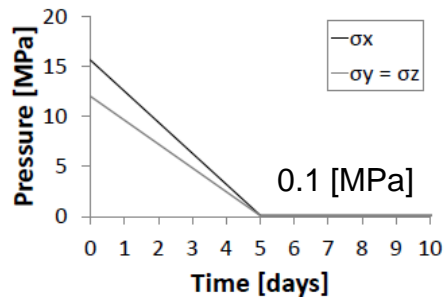
Mechanical modelling in 3D state.

Classical FE, no second gradient !

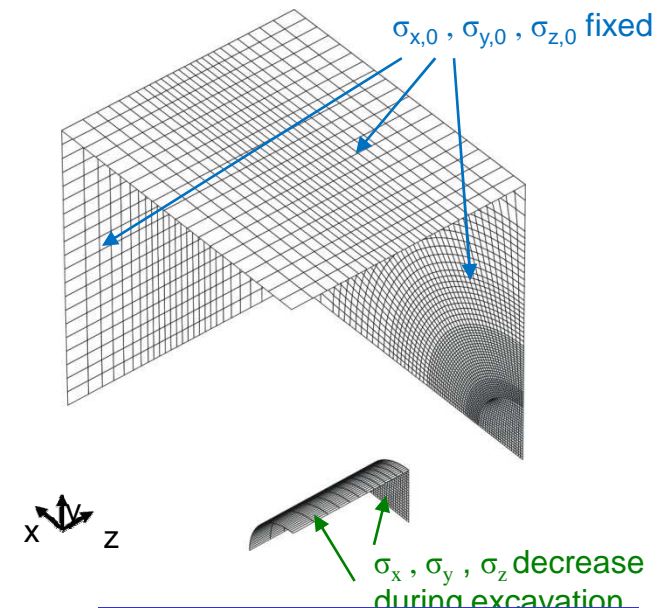
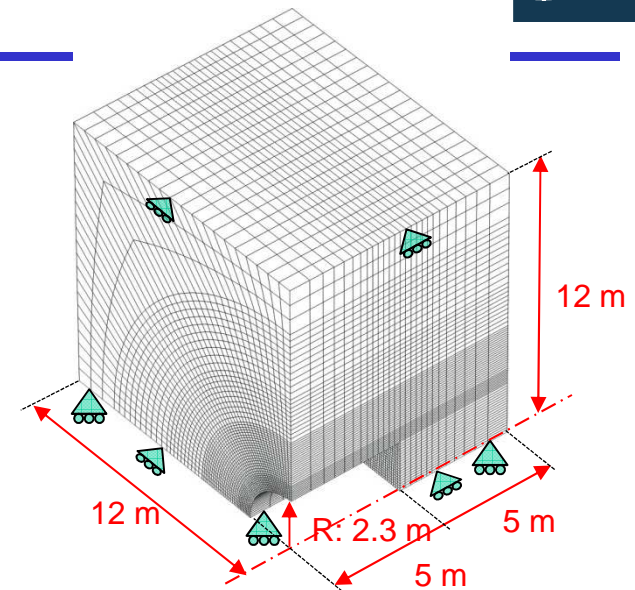
Initial anisotropic stress state (Andra URL) :

$$\begin{aligned} \sigma_{y,0} &= \sigma_{z,0} = 12 \text{ [MPa]} \\ \sigma_{x,0} &= 15.6 \text{ [MPa]} \end{aligned}$$

Identical excavation :

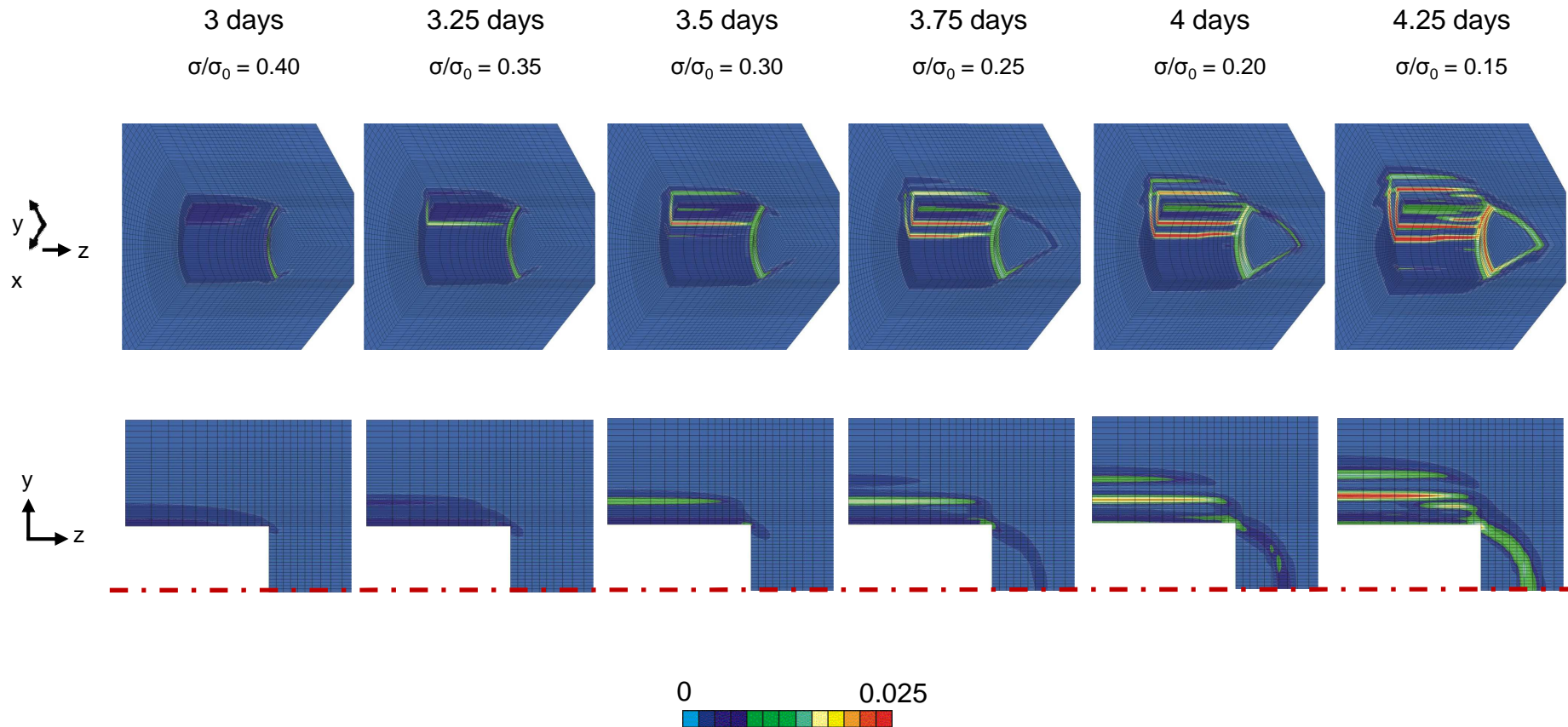


Mesh :  
 410 591 nodes  
 60 320 volume elements with 20 nodes  
 4 480 elements of stress imposition  
 752 226 equations  
 8 days of calculation



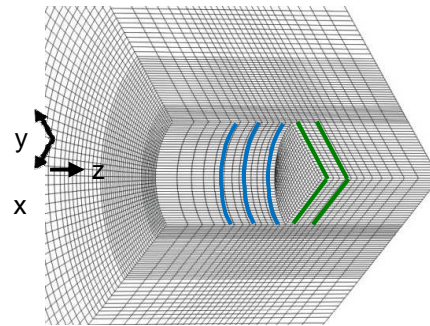
## Equivalent deformation $\epsilon_{eq}$ :

$\epsilon_{eq}$  during boring :

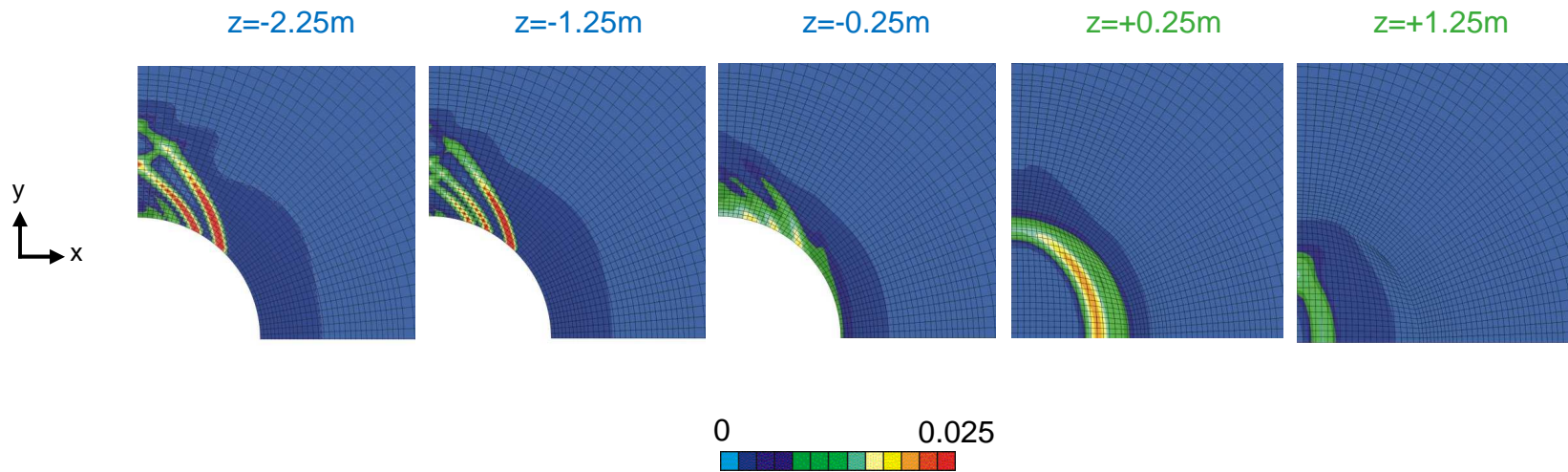


## Equivalent deformation $\epsilon_{eq}$ :

$\epsilon_{eq}$  for 4.25 days of excavation ( $\sigma/\sigma_0 = 0.15$ ) :



z<0 : excavation zone  
z=0 : gallery end  
z>0 : rock mass



- 
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### Thanks to:

A. Dizier, PhD Student (2011)

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J.P. Radu, Senior Researcher

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EU TIMODAZ Project

EU FORGE Project