# Addressing caprock failure tendency in deep saline aquifers through large scale hydromechanical analysis – Application in the Paris Basin case

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vendredi 12 juin 2009

# Introduction

> **Injection of supercritical Co2**

→ **changes in the effective stress components {σ'3 ; σ'1} surrounding the aquifer reservoir (e.g. Rutqvist et al., 2007 ; Vidal-Gilbert et al., 2008)**

> → **Potential caprock failure (creation of new fractures or reactivation of pre-existing fractures)**

→ Potential pathways for the Co2 to escape from the aquifer reservoir

→ Potential risks for the humans and the environment (Holloway, 1997)

→ Decrease of the efficiency of the storage to mitigate climate change

> **Huge amount of uncertainties on the caprock properties (hydraulic and mechanical)**

→ They have seen less exploration than caprocks of Oil and Gas reservoirs

→ They have not proven to confine buoyant fluids for geological time scale as for Oil and Gas reservoirs

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# Introduction

1. Caprock failure assessment methodology

2. Description of the large scale hydromechanical model of the Paris basin case

3. Methodology to deal with the lack of knowledge of the caprock layer

4. Caprock failure assessment in the injection zone at the interface between the caprock and the reservoir layer

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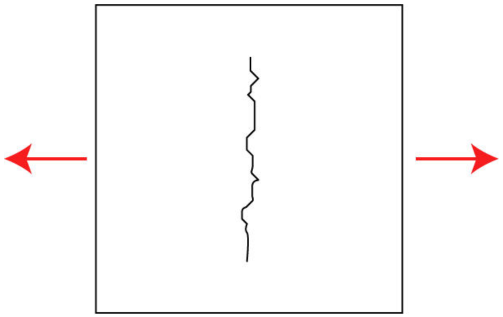
# Cap Rock failure mechanism

**Failure mechanism n°1**
**Tensile Fracturing**

$$\sigma'_3 \leq 0$$



*Assumption :*
*tensile strength Rt = 0*

*See for instance: Rutqvist et al., 2007*

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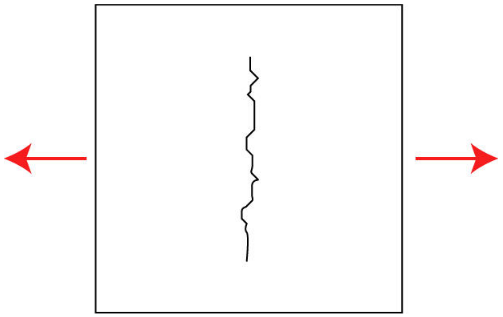

*Assumption :*
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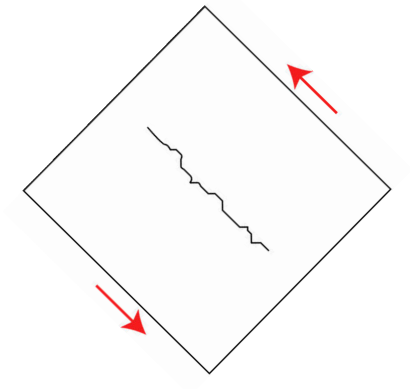
**Failure mechanism n°2**
**Shear slip**

$$\sigma'_1 / \sigma'_3 \ge q$$



*Assumption :*
*Pre existing fracture with no cohesion*
*$q \approx 2$ for a angle of internal friction $\varphi'$ of 20°*

*See for instance: Rutqvist et al., 2007*

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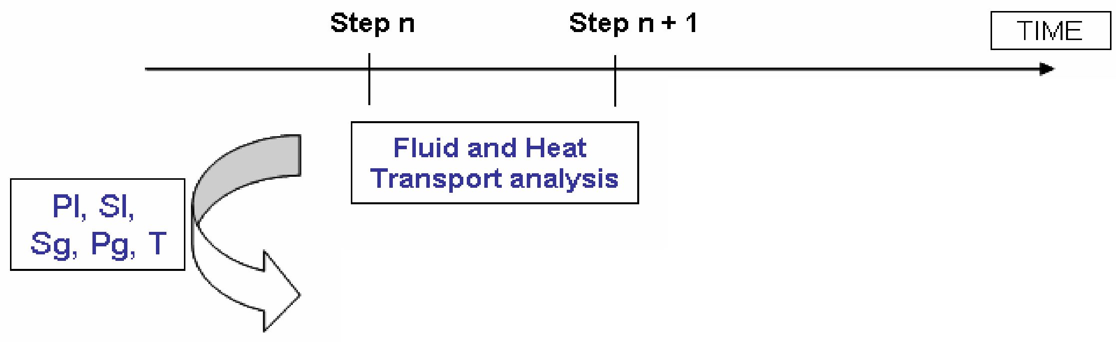
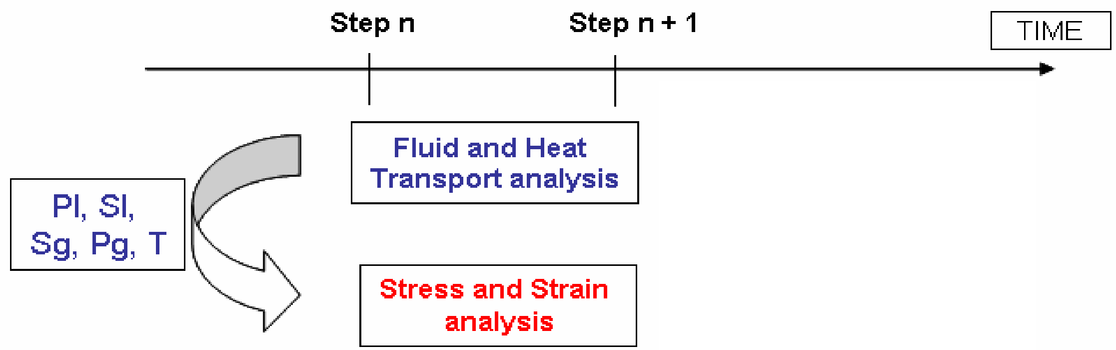
# Methodology : sequential coupling




## > Fluid and Heat Transport analysis

- Tough2 (Pruess et al., 1999)
- Fluid property module ECO2N of water–NaCl–CO2 mixtures (Pruess, 2005)

# Methodology : sequential coupling




$$\underline{\underline{\sigma}}' = \underline{\underline{\sigma}} - bP\underline{\underline{I}}$$

*b Biot coefficient, P pore pressure, σ' effective stress, σ total stress (e.g. Coussy, 1995)*

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## > Stress and Strain analysis

- Finite element thermo-hydro-mechanical calculation code : Code_Aster® (*e.g.* Chavant *et al.*, 2002)

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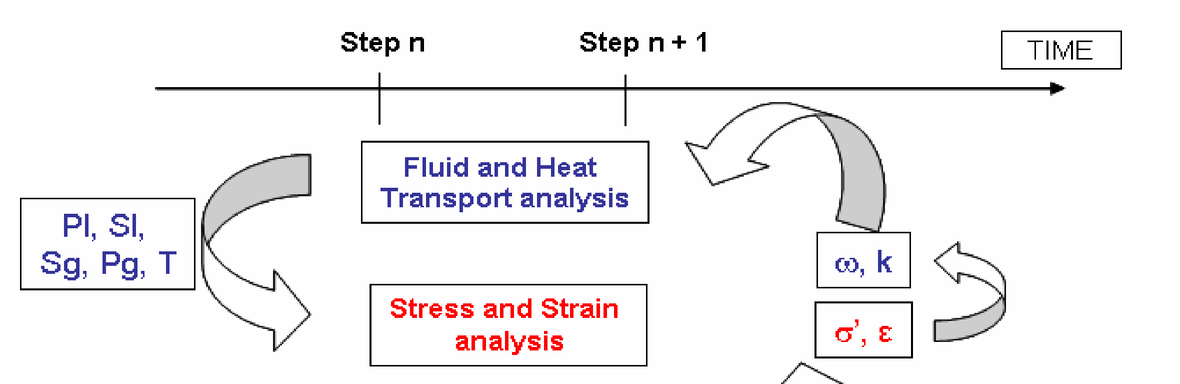


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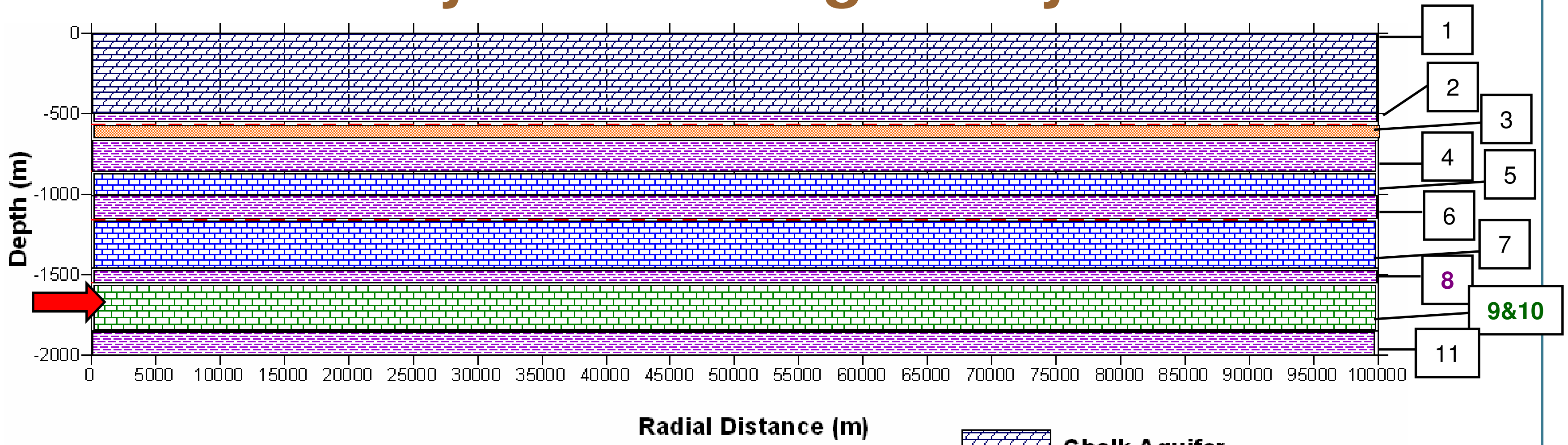
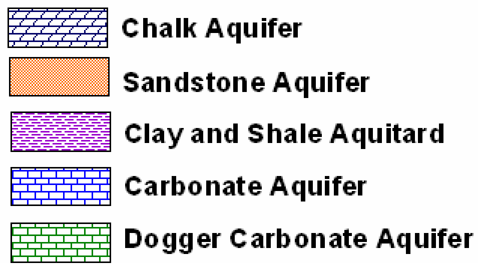
# Paris = Multilayered Geological System




| Layer | Lithology | Geological unit | Thickness (m) | Depth (m) | Hydrostratigraphy |
|---|---|---|---|---|---|
| N°1 | Chalk | Upper Cretaceous | 500 | 500 | Semi permeable |
| N°2 | Clay and Shale | Albian and Cenomanian | 60 | 560 | Low permeable |
| N°3 | Sandstone | Albian | 100 | 660 | High permeable |
| N°4 | Clay and Shale | Lower Cretaceous and Purbeckian | 200 | 860 | Low permeable |
| N°5 | Limestone | Thitonian | 150 | 1010 | High permeable |
| N°6 | Shale | Kimmeridgian | 150 | 1160 | Low permeable |
| N°7 | Limestone | Oxfordian and Kimmeridgian | 300 | 1460 | High permeable |
| N°8 | Clay and Shale | Oxfordian and Callovian | 90 | 1550 | Low permeability |
| N°9 | Limestone | Upper Dogger | 150 | 1700 | High permeable |
| N°10 | Limestone (tight) | Lower Dogger | 150 | 1850 | Semi to low permeable |
| N°11 | Clay | Lias | 400 | 2250 | Low permeable |

Caprock layer

Reservoir layer

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Based on the PICOREF project (Grataloup et al., 2008)

# Co2 Injection Scenario

- Injection rate: 320 kg/s of supercitical Co2 ⇔ ~10 Mt / y during 10 years
- Axisymmetric model
- Large extent of 100 km
- Initial hydrostatic pressure
- Isothermal behaviour gradT=0.041 °C/m
- Salinity of 35 g/l in the Dogger reservoir
- No mechanical effect on the hydraulic properties
- No pore diffusivity
- No geochemical degradation
- In particular, hydraulic and mechanical properties of the Dogger reservoir based on measurements for geothermal activities (Rojas et al., 1989, Andre et al., 2007)

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# Uncertainty on the Caprock hydraulic properties

**Observation :** ***the caprock properties have an important influence on the overpressure at the interface with the reservoir aquifer layer (Birkholzer et al., 2009)***

**Objective : define the caprock properties so that the overpressure is maximum = critical configuration**

| Property | Symbol | Lower bound | Upper bound | Unit | Reference |
|---|---|---|---|---|---|
| **Intrinsic permeability** | *Kh* | **5.e-5** | **1.0** | mD | Lab test of the Geocarbone Integrity project, Fleury et al., 2007<br>Andra, 2005 |
| **Permeability anisotropy** | *A* | **1/100** | **1/10** | (-) | Assumed |
| **Porosity** | $\omega$ | **5** | **15** | % | Lab test of the Geocarbone Integrity project, Fleury et al., 2007 |
| **Van Genuchten parameter** | $P_0$ | **1** | **8** | MPa | Lab test of the Geocarbone Integrity project, Fleury et al., 2007 |
| **Van Genuchten parameter** | $\lambda$ | **0.330** | **0.600** | (-) | Andra, 2005<br>Andre et al., 2007 |
| **Residual Water saturation** | *Slr* | **20** | **30** | % | Bachu and Bennion, 2007<br>Birkholzer et al., 2009 |
| **Residual Gas saturation** | *Sgr* | **5** | **35** | % | Bachu and Bennion, 2007<br>Birkholzer et al., 2009 |
| ***Pore compressibility*** | *C* | **4.5e-10** | **9.0e-10** | Pa-1 | Birkholzer et al., 2009 |

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# Methodology

**Response surface method (Box and Draper, 1987)**

**Step 1 « training data »: simulate the injection for a finite number of configurations of the caprock properties**

- **Configurations of the caprock properties are randomly generated (Latin Hypercube Sampling method, McKay et al., 1979)**

**Step 2 « approximation »: of the pressure build up by means of a linear regression model**

- **Coefficient of determination $R^2$=92 %**

**Step 3 « validation »: of the approximation quality through Leave One Out Cross Validation Procedure LOOCV (e.g. Hjorth, 1994)**

- **Coefficient of determination $R^2$=85 %**

**Step 4 « Critical configuration » : for which the overpressure in the injection zone is maximum**

- **« Worst case » cf. EC Directive on CCS operations (Annex I, *3.3.4* Risk characterisation)**

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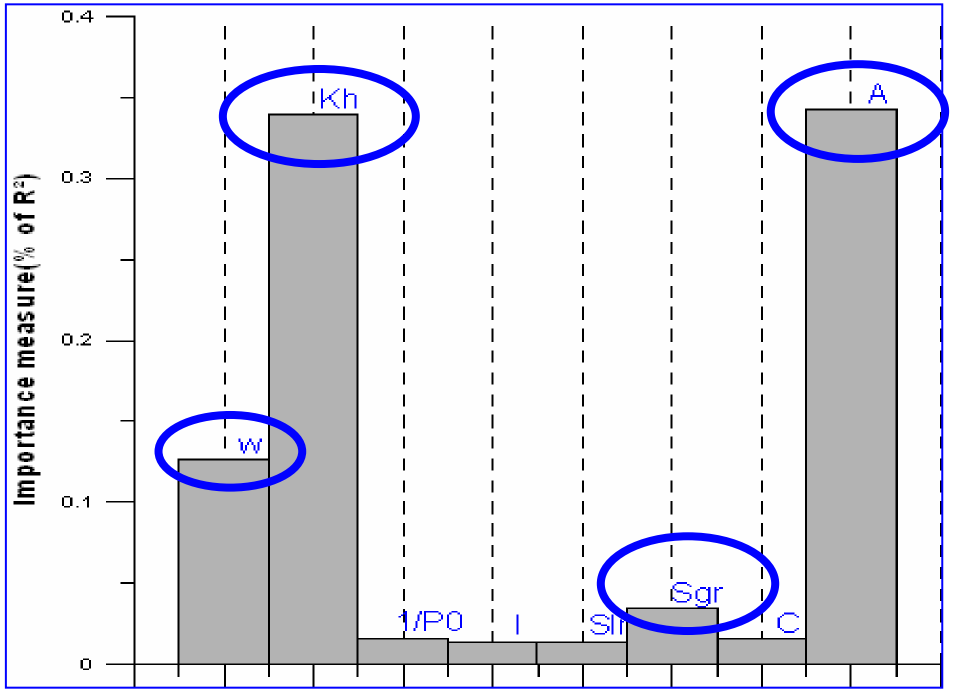
# Critical configuration of Caprock hydraulic properties




| Most sensitive Property | Configuration for Minimum Overpressure | Configuration for Maximum Overpressure | Unit |
|---|---|---|---|
| **Porosity ω** | 15 | 5 | % |
| **permeability Kh** | 1.0 | 5.e-5 | mD |
| **Residual Gas Saturation Sgr** | 35 | 5 | % |
| ***Anisotropy A*** | 1/10 | 1/100 | (-) |

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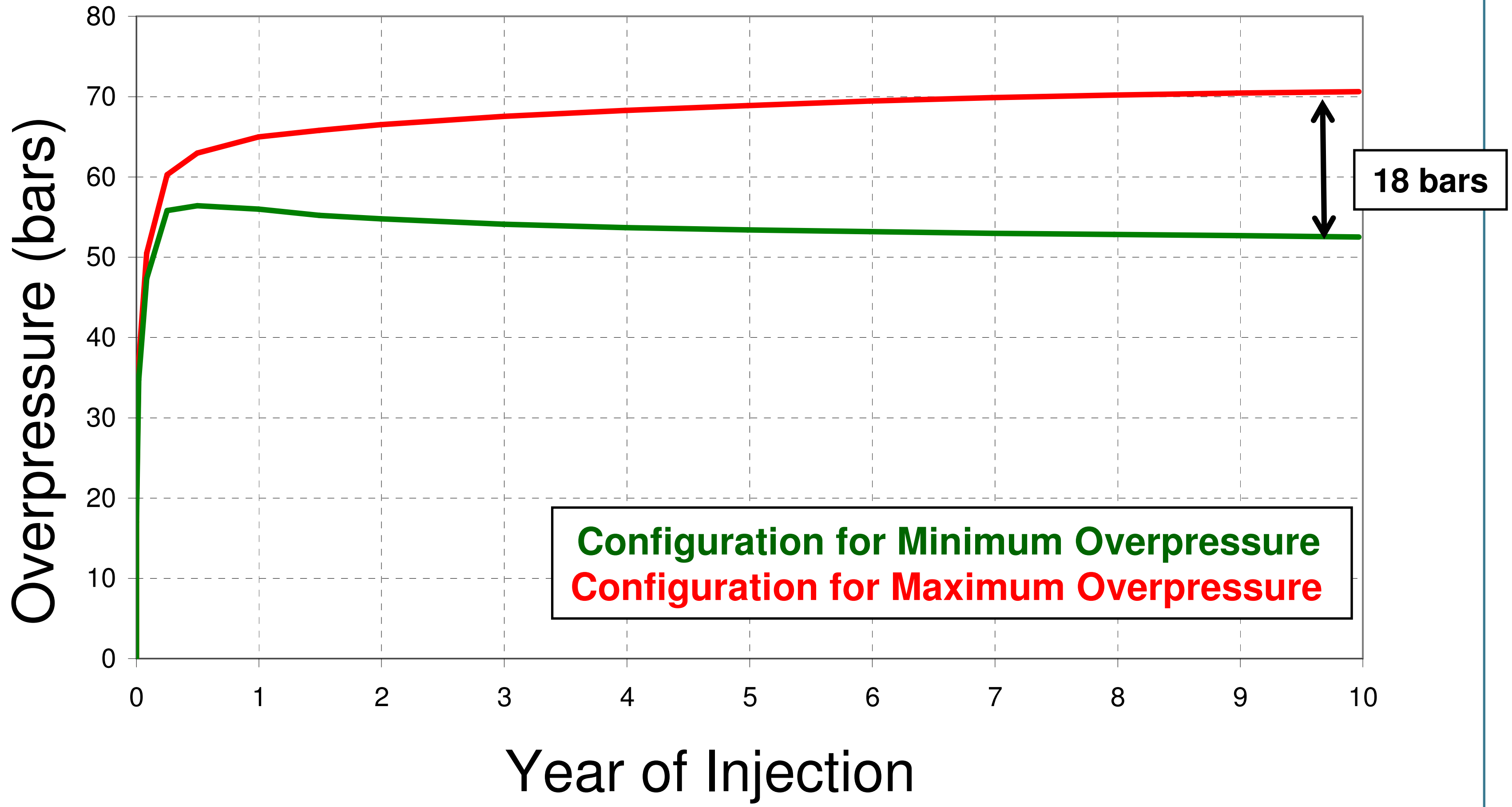
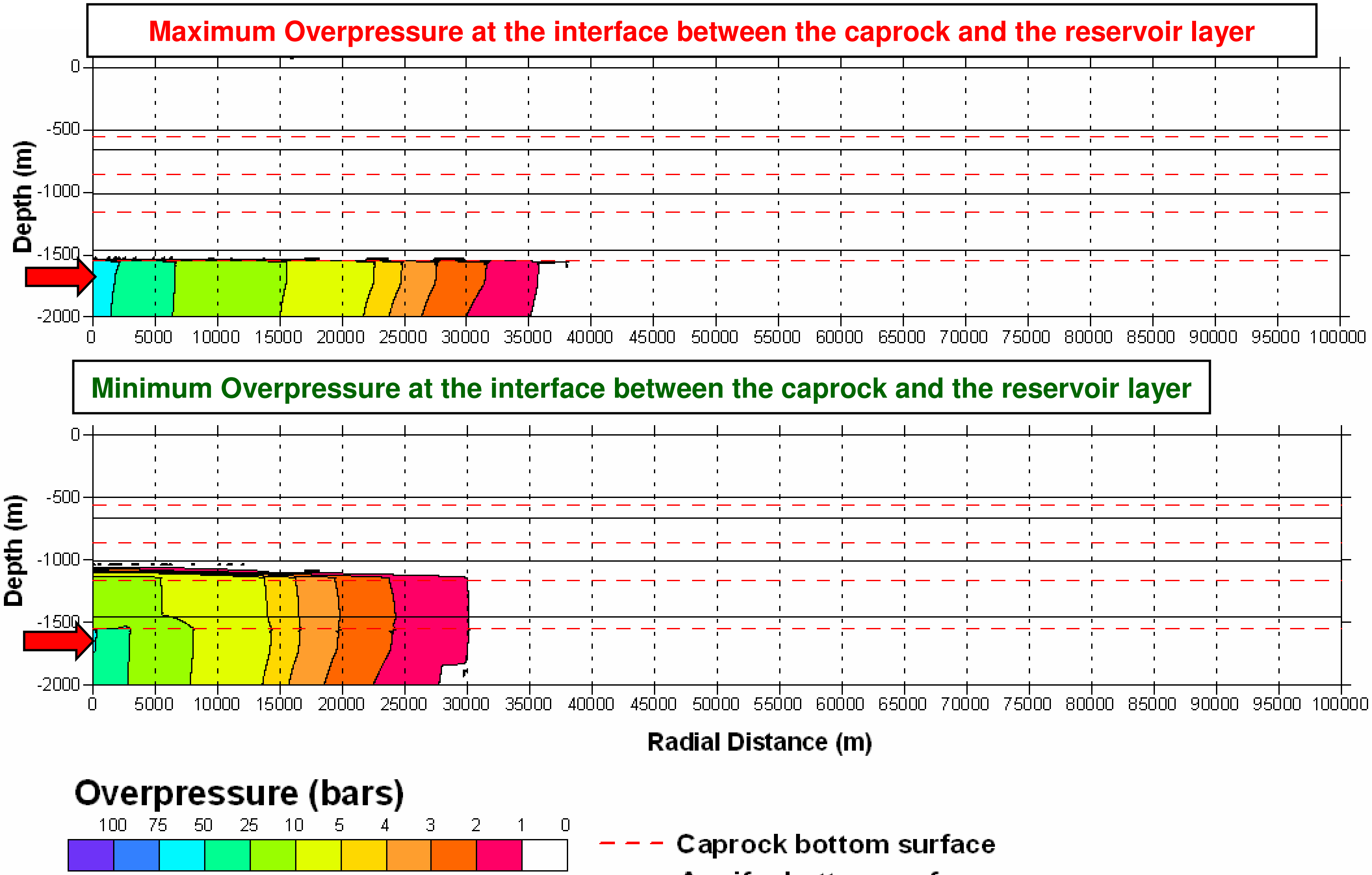
# Overpressure evolution in the injection zone at the interface betw. the reservoir and the caprock layer



# Overpressure after 10 y of injection

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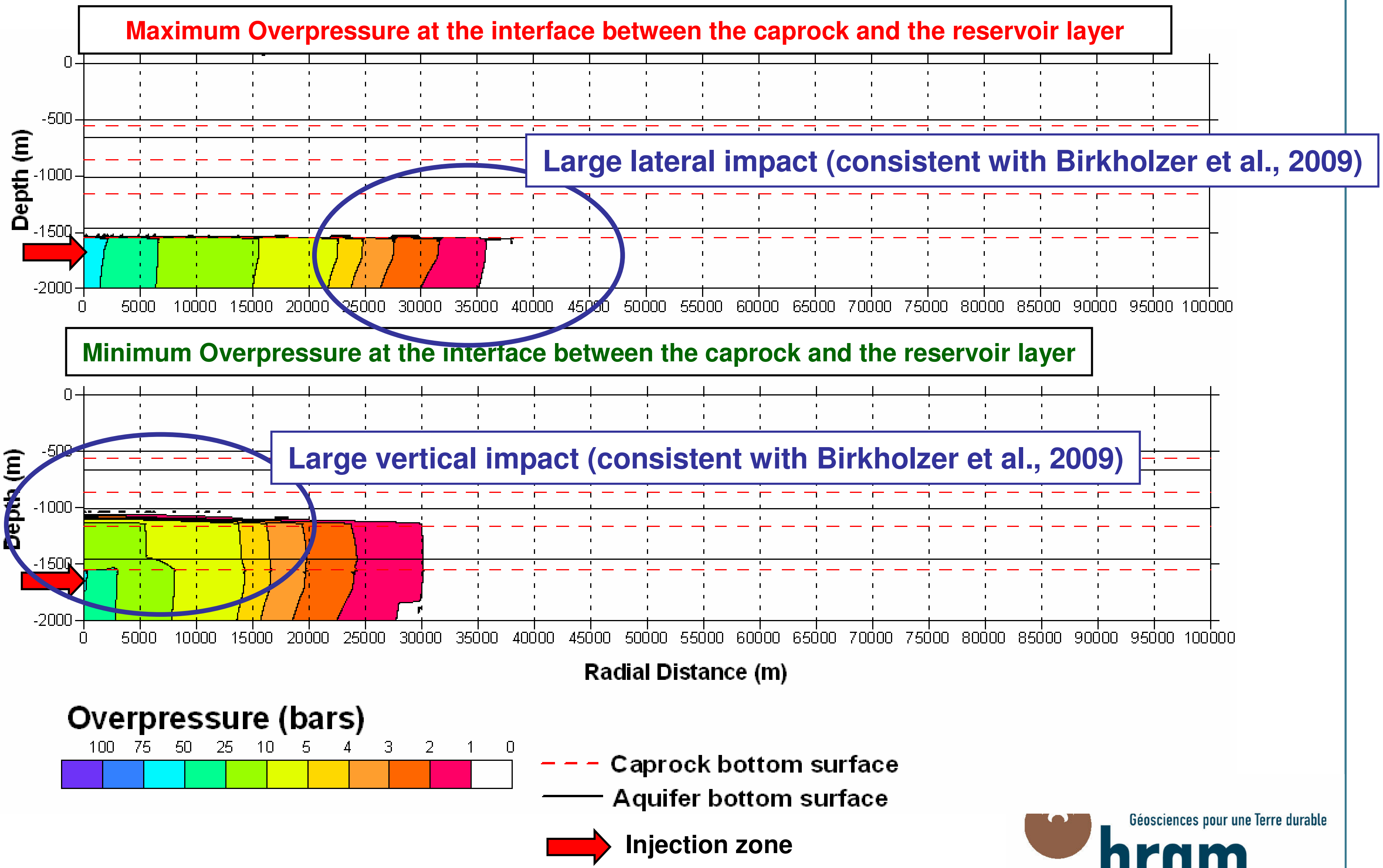

# Uncertainty on the Caprock mechanical properties

| Property | Symbol | Lower bound | Upper bound | Unit | Reference |
|---|---|---|---|---|---|
| **Young's Modulus** | $E$ | 2.3 | 11.0 | GPa | Andra, 2005 and Bounneni, 2002 |
| ***Poisson's ratio*** | $\upsilon$ | 0.17 | 0.40 | GPa | Andra, 2005 and Bounneni, 2002 |

Objective : define the caprock elastic properties so that the caprock failure risk is MAX

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Objective : define the caprock elastic properties so that the caprock failure risk is MAX

**Step 1 « training data »:**
Configurations of the caprock mechanical properties are randomly generated

**Failure mechanism n°1**
**Tensile Fracturing**

$$\sigma'_3 \leq 0$$

**Step 2 « approximation »** by a linear regression model
Coefficient of determination $R^2$=98.4 %

**Step 3 «  validation »:**
Coefficient of determination $R^2$=94.53 %

**Step 4 « Critical configuration »:**
- Importance measure of the Poisson's ratio =  94.67 %
- minimum $\sigma$'3 for $\upsilon$=0.40

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**Failure mechanism n°2**
**Shear slip**

$$\sigma'_1 / \sigma'_3 \geq q$$

**Step 2 « approximation »** by a linear regression model
Coefficient of determination $R^2$=99.23 %

**Step 3 « validation »:**
Coefficient of determination $R^2$=97.27 %

**Step 4 « Critical configuration »:**
- Importance measure of the Poisson's ratio = 94.61 %
- σ'1 /σ'3 is maximum for υ=0.40

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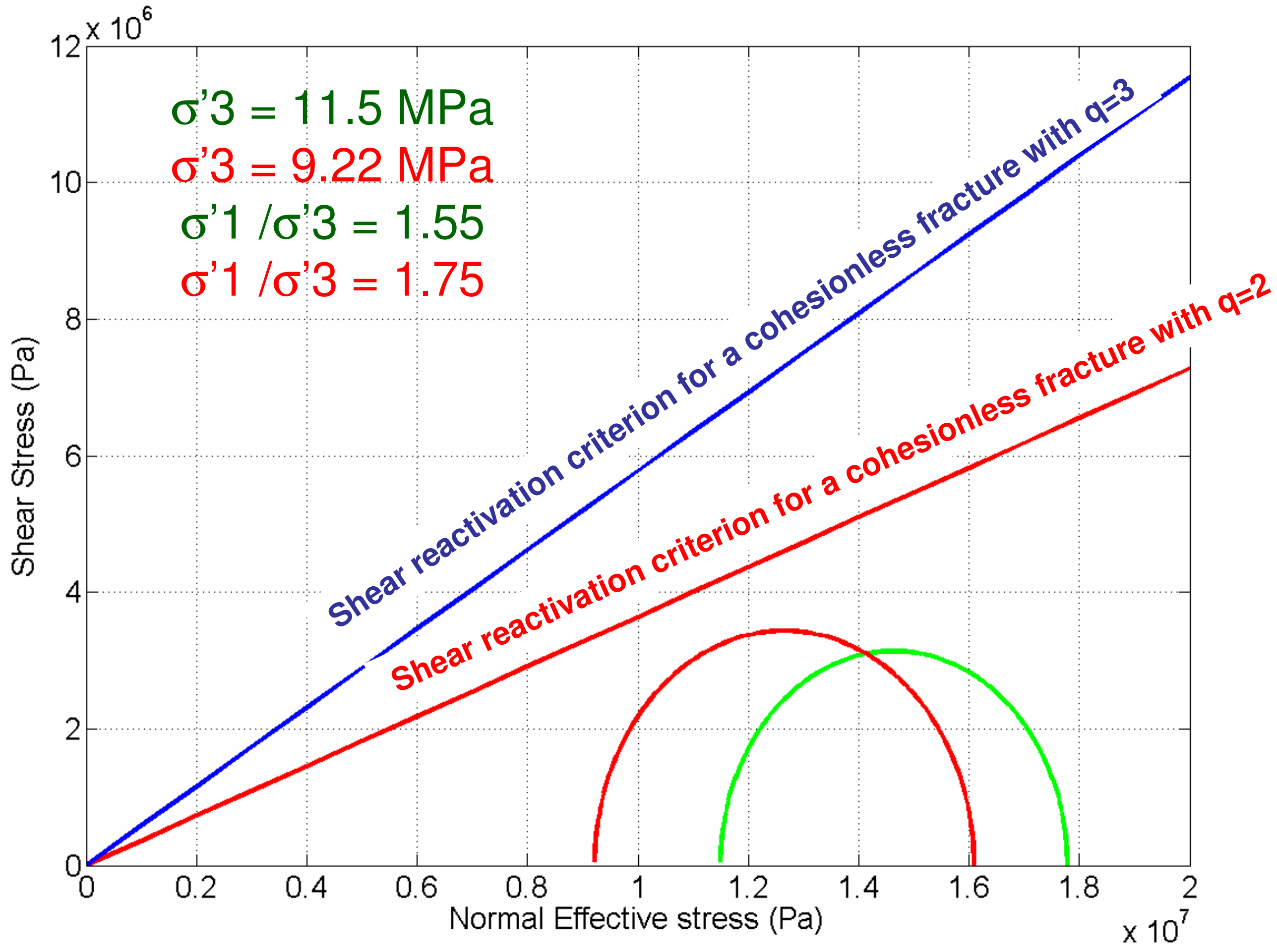
# Mohr circle in the injection zone at the interface betw. the reservoir and the caprock layer

**Initial ratio betw. horizontal and vertical stress = 0.60 (Vidal-Gilbert et al., 2008)**

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# Concluding remarks

> **The injection-induced overpressure is maximal** in the injection zone (distance < 100 m) =most critical one in the system.

> The **lateral extension** of the “overpressurized” region is large (> 50 km).

> **Tensile fracturing mechanism** is not activated even for the worst case of the caprock properties

> **Shear slip reactivation** of pre-existing cohesionless fractures might be possible but for low friction angle ($q<2 \leftrightarrow \varphi'<20°$) for the worst case of the caprock properties

> **Further works:**

- Failure assessment of the aquifer/aquitard layers in case of vertical pressure impact
- Thermal effect
- Include faults as cohesive elements
- Application of the methodology to identify the worst case of the whole multilayered geological system

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***Thank you for your attention !***

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# Annex

- Annex 1 : Co2 saturation field
- Annex 2 : table of properties
- Annex 3 : cross validation
- Annex 4 : modelling the Dogger reservoir

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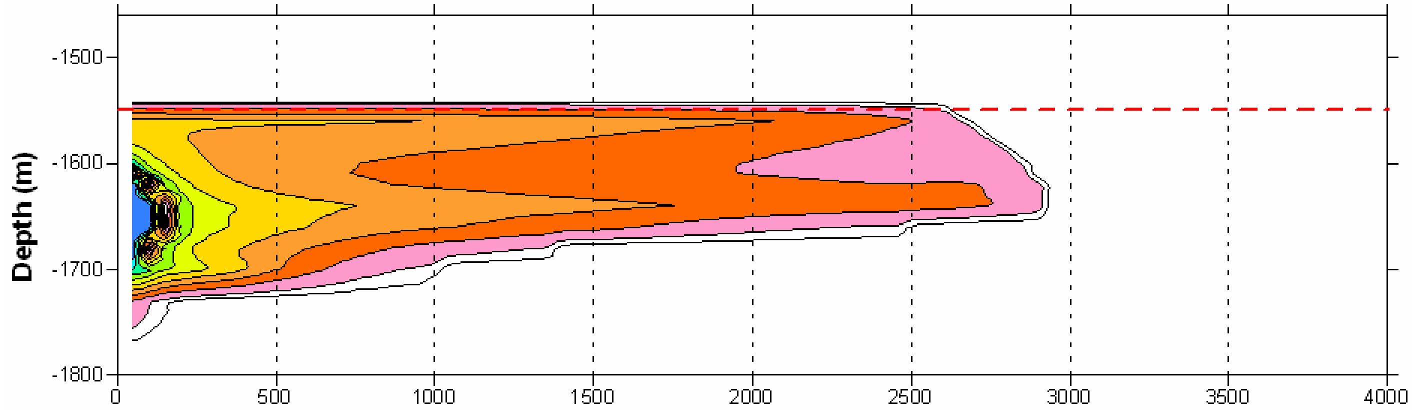
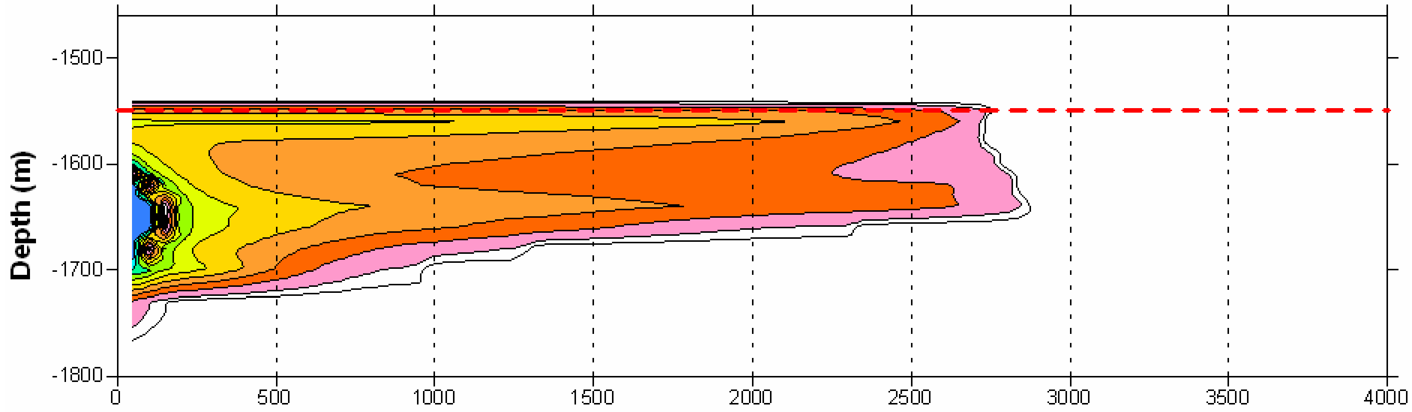
# Annex 1

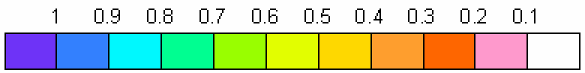
### Maximal Ovepresssure




### Minimal Overpressure




## Co2 saturation




Caprock bottom surface

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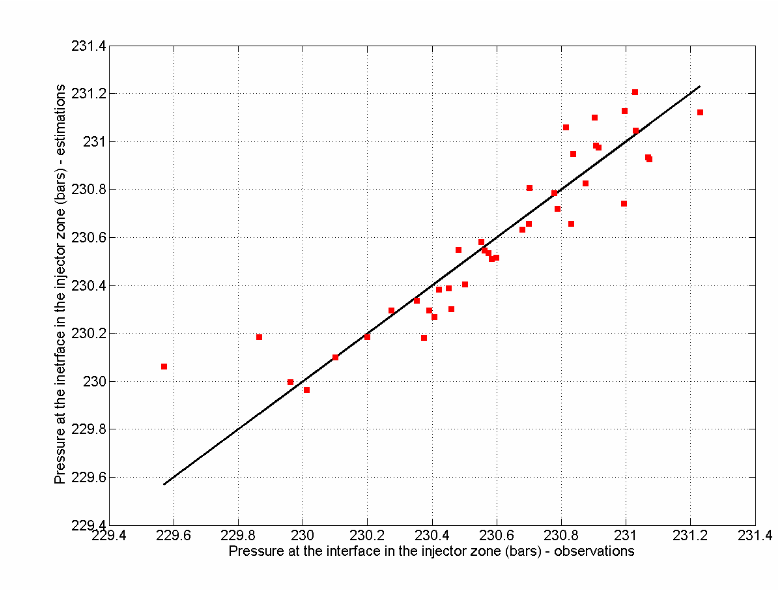
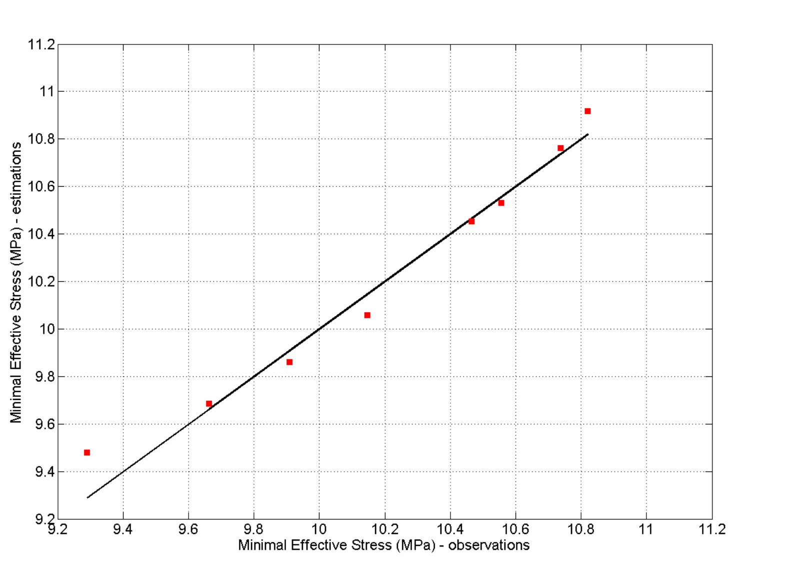
# Annex 2

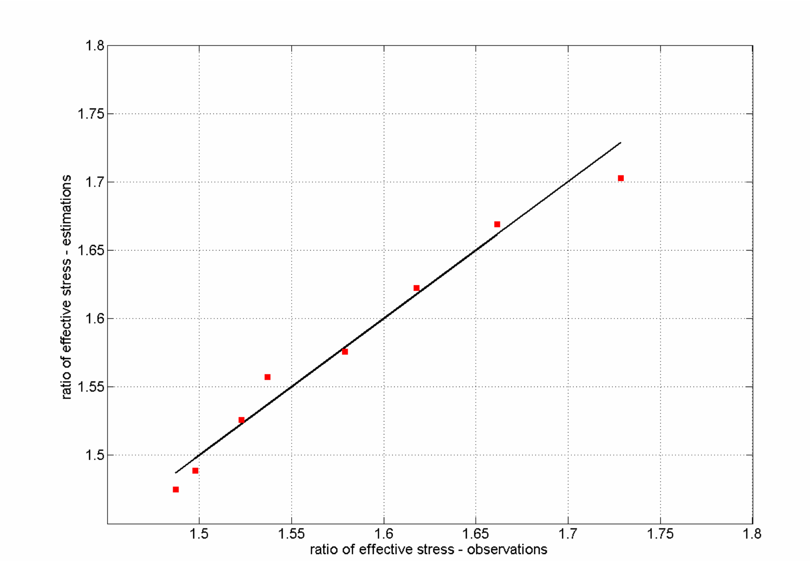
| Layer | Van Genuchten's parameter λ | Residual liquid saturation [%] | Residual gas saturation [%] | Air entry pressure [bars] |
|---|---|---|---|---|
| **Carbonate aquifers and Chalk aquifer** | 0.600 | 20 | 5 | 0.54 |
| **Sandstone aquifer** | 0.750 | 1.5 | 20 | 0.0358 |
| **Clay and Shale interlacing layers** | 0.329 | 30 | 5 | 50 |
| **Caprock layer** | 0.329 | 30 | 5 | 80 |
| **Reservoir layer** | 0.600 | 20 | 5 | 0.54 |
| **Lower Dogger formation** | 0.600 | 20 | 5 | 10 |

| Layer | Young Modulus [GPa] | Poisson ratio [-] | Intrinsic permeability [mD] | Ratio between horizontal and vertical permeability | Porosity [%] |
|---|---|---|---|---|---|
| **Chalk aquifer** | 5 | 0.3 | 1 | 1 | 30 |
| **Clay and Shale interlacing layers** | 6.65 | 0.285 | 0.001 | 10 | 5 |
| **Sandstone aquifer** | 10 | 0.3 | 50000 | 2 | 25 |
| **Carbonate aquifers** | 15 (upper)<br>20 (lower) | 0.3 | 100 | 1 | 15 |
| **Caprock layer** | 6.65 | 0.285 | 0.00005 | 10 | 5 |
| **Dogger formation (reservoir)** | 24 | 0.29 | 705 for the high productive layer<br>90 for the low productive layer | 10 | 15 |
| **Lower Dogger formation** | 42 | 0.29 | 1 | 10 | 10 |

# Annex 3

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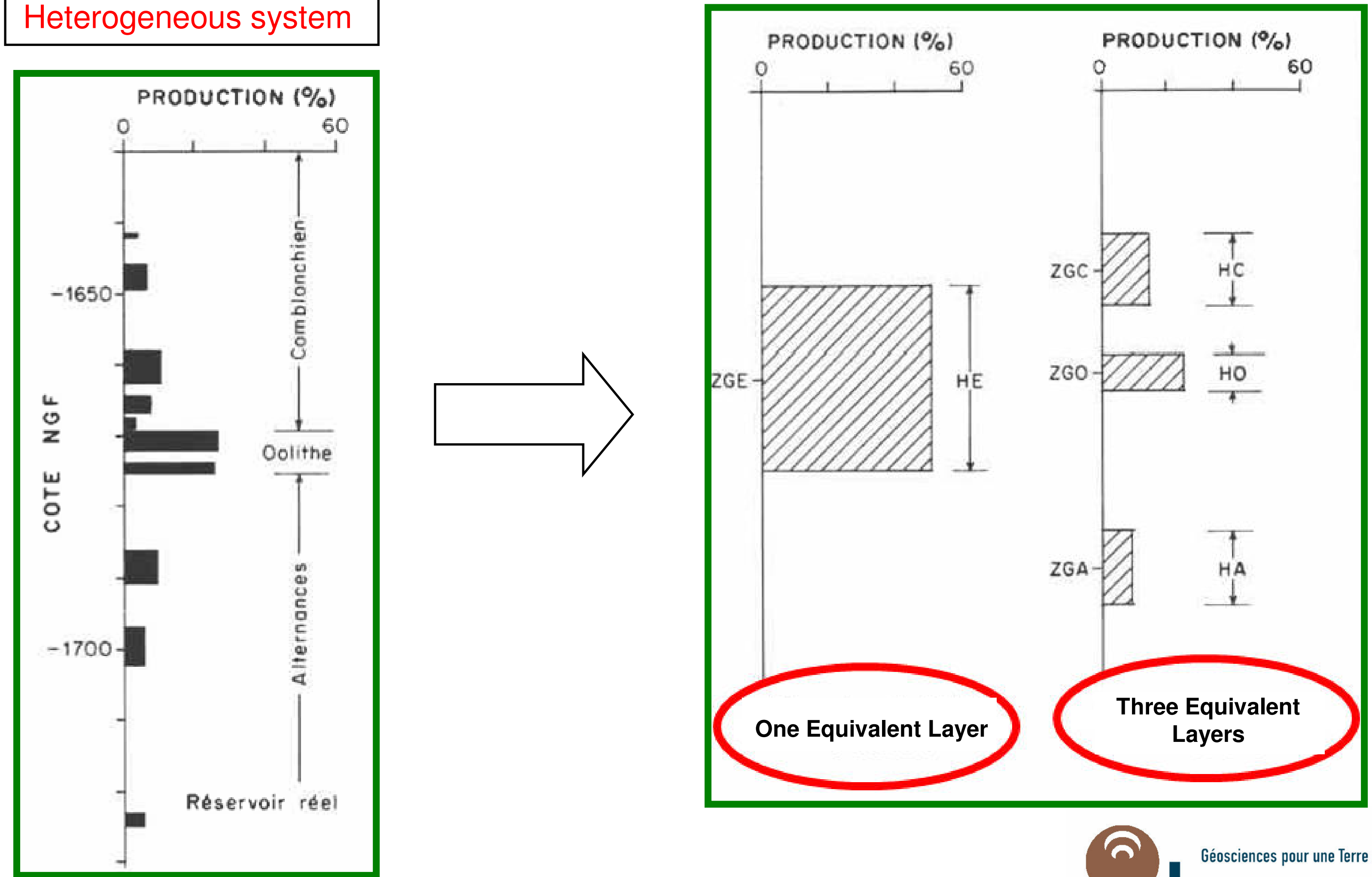
# Annex 4

Heterogeneous system




*Production Tests for geothermal activities, Rojas et al., 1989*

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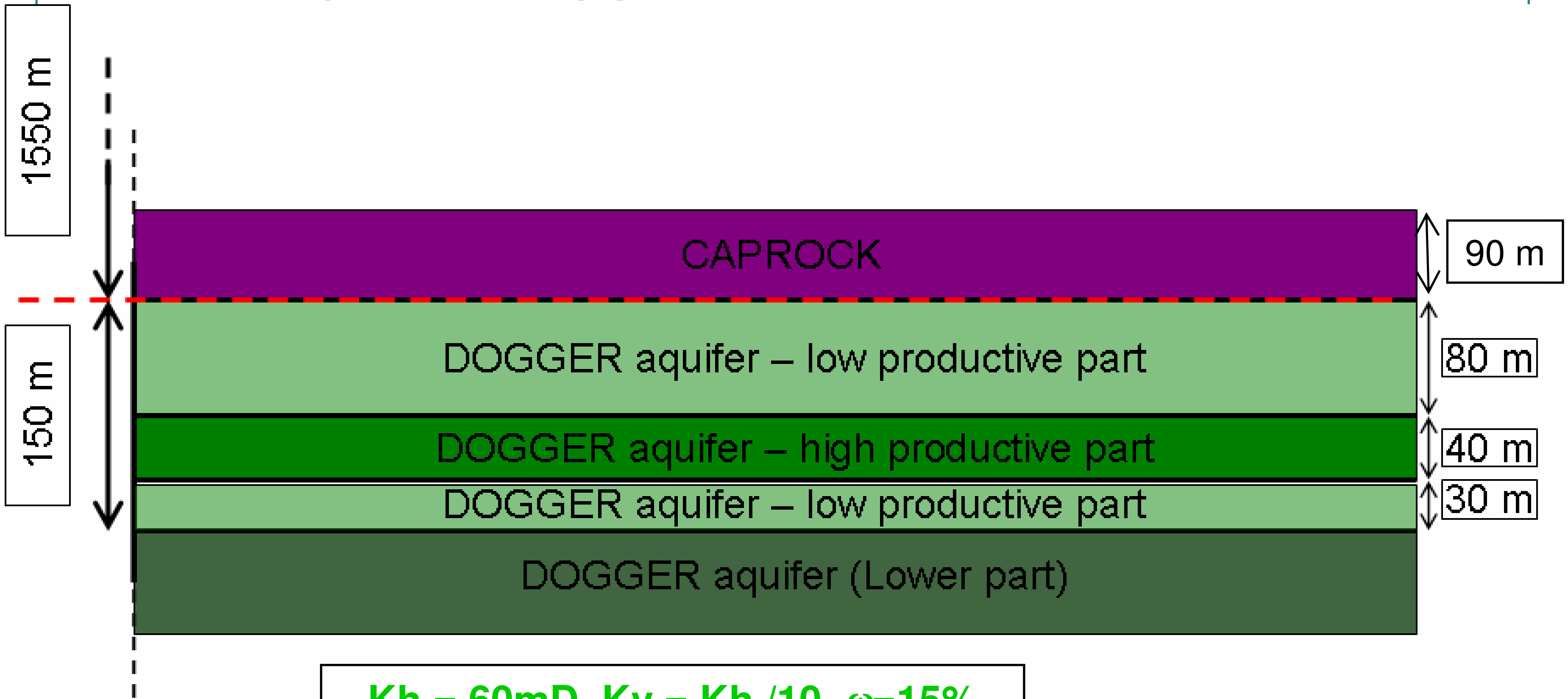
# Modelling the Dogger reservoir




**Kh = 60mD, Kv = Kh /10, ω=15%**
**Kh = 200mD, Kv = Kh /10, ω=15%**
**P0 = 54 000 Pa, Slr = 20 %, λ=0.600**

⇨ **Transmissivity ≈ 14.6 D.m**

*Rojas et al., 1989 , Andre et al., 2007*

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