Bruface
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Hydro-mechanical modeling of CO_2 sequestration in deep saline aquifers

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Introduction

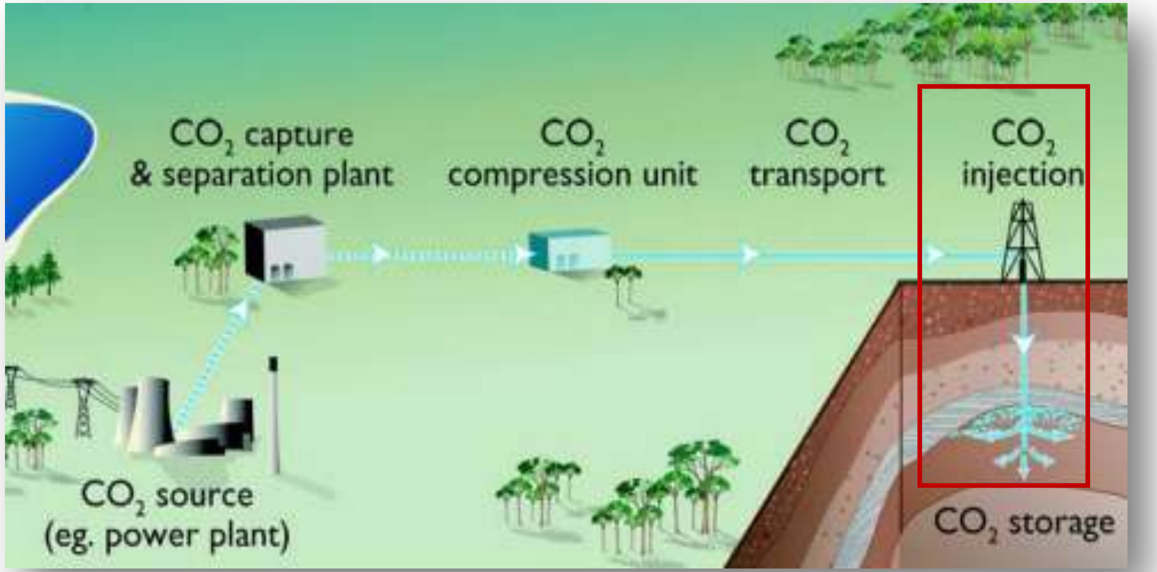
- Global warming ➔ Technologies to reduce **CO_2 emissions**

- **Carbon Capture & Sequestration (CCS)**

- **Deep geological reservoirs:**

  1) large porosity ➔ good storage capacity

  2) large permeability ➔ good injectivity



(CO_2CRC)

E.g. **deep saline aquifer** (in sandstone)

Introduction

➢ **CO_2 condition**

Reservoir depth ↑ (z>800m)

↓

P&T ↑

↓

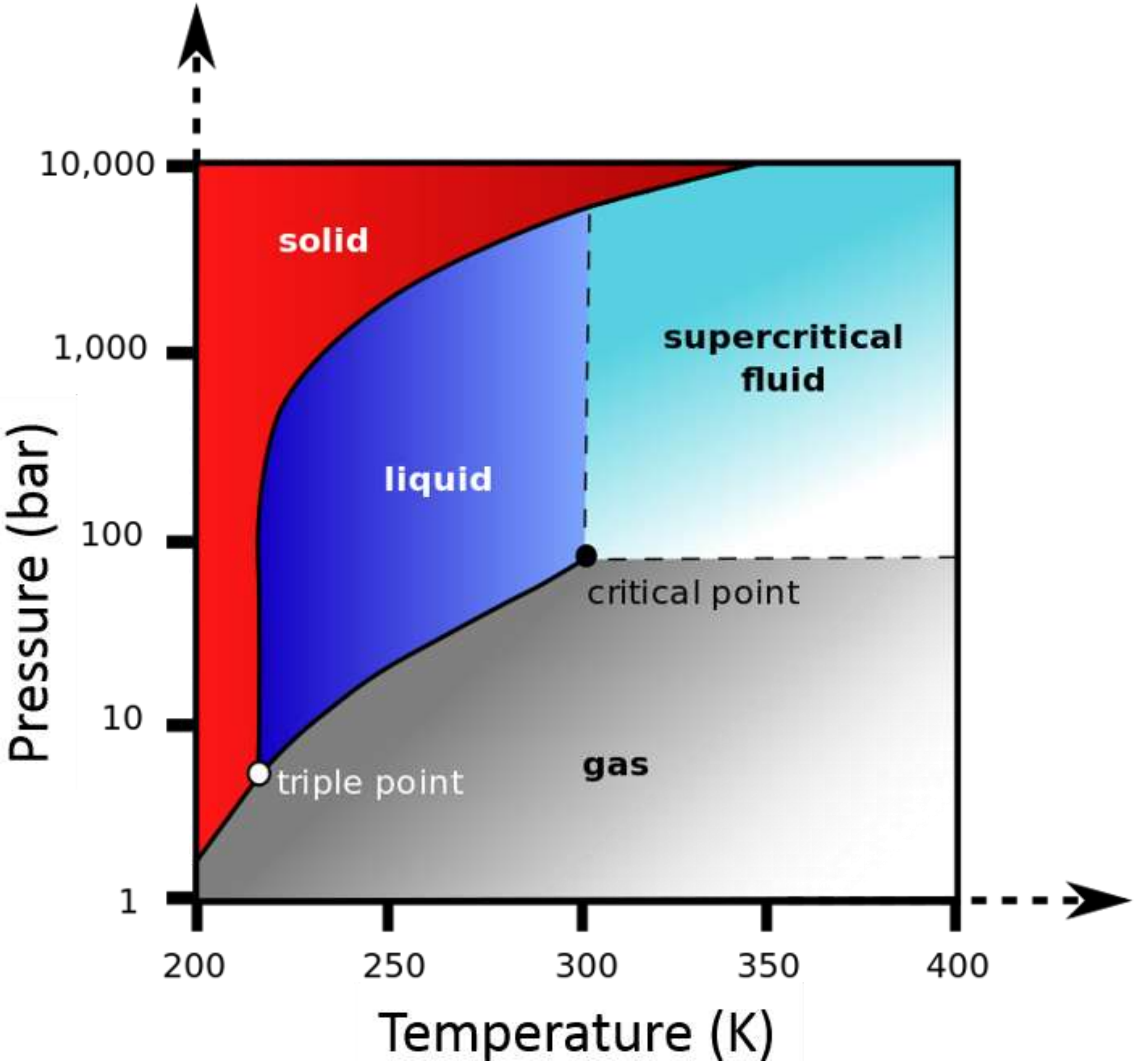
supercritical CO_2

↓

ρ_{CO_2}↑

↓

storage efficiency ↑



(en.wikipedia.org)

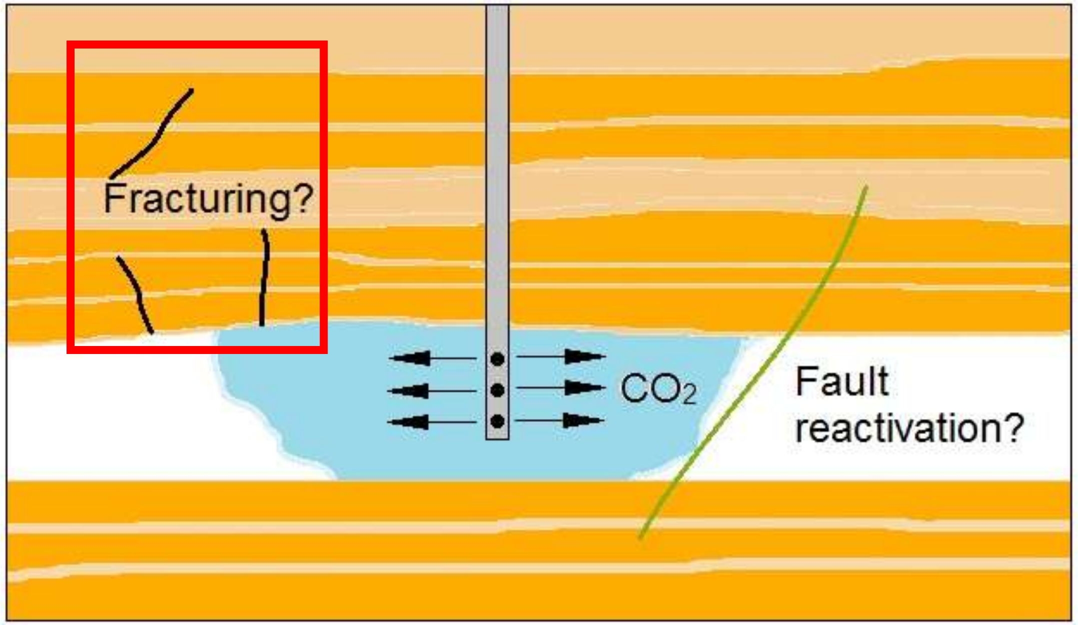
Introduction

- **Geomechanical issues**

Hydro-mechanical coupling:

CO_2 injection ➔ ΔP_{fluid} ➔ $\Delta\sigma'$ ➔ ε

failure of reservoir?



(Rutqvist, 2012)

- **Objectives**

  - **Numerical modeling** of **Hydro-mechanical effects** during CO_2 sequestration in **simplified deep saline aquifer**

  - Impacts on reservoir **mechanical stability** & CO_2 **injection efficiency**

(Modeling tool: Finite element code **LAGAMINE**)

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Introduction	Hydro-mechanical model	Numerical model	Conclusion
• CCS • Geomechanical issues • Objectives	• H model • M model	• 1D H model • 1D HM model • 2D H model	• Remarks • Perspectives

Hydro-mechanical model

- **Isothermal conditions** (T=320 K)

- **Hydraulic model :**

2-phase flow
- **Liquid phase**
  - Liquid water
  - $CO_{2\text{-}d}$
- **Gas phase** → $CO_{2\text{-}sc}$

- **Mass Flux balance**

$$\underline{f}_{\mathrm{w}} = \rho_w \underline{q}_l$$

$$\underline{f}_{CO_2-SC} = \rho_{CO_2-SC} \underline{q}_g$$

$$\underline{f}_{CO_2-d} = \rho_{CO_2-d} \underline{q}_l + \underline{i}_{CO_2-d}$$

Flows of advection *(Darcy's law)*

$$\underline{q}_g = -\frac{kk_{r,g}}{\mu_{CO_2-SC}}(\nabla P_{\mathrm{g}} + \rho_{CO_2-SC} g \nabla z)$$

$$\underline{q}_l = -\frac{kk_{r,\mathrm{w}}}{\mu_w}(\nabla P_w + \rho_w g \nabla z)$$

Flows of diffusion *(Fick's law)*

$$\underline{i}_{CO_2-d} = D\tau\phi\nabla C_{CO_2-d}$$

- We need to define **parameters** in the model: S_r, k, ρ, μ, etc.

Hydro-mechanical model

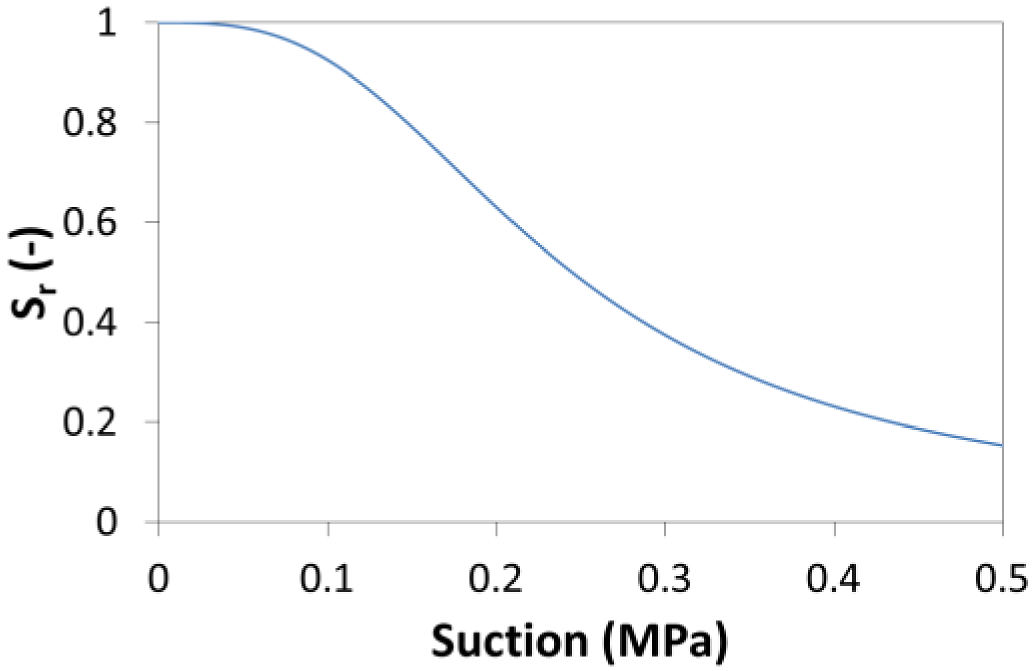
➢ **Hydraulic properties**

- **Retention curve**

van Genuchten law:

$$S_r = \left(1 + \left(\frac{P_c}{P_r}\right)^n\right)^{\frac{1}{n}-1}$$

Retention curve



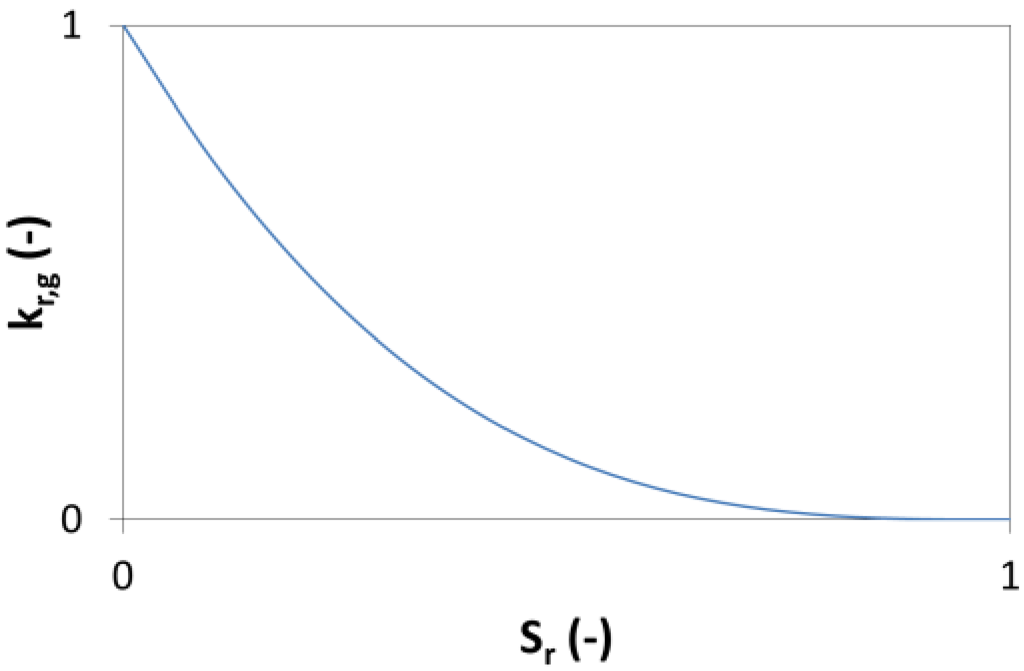
- **Relative permeability**

Cubic law:

$$k_{r,w} = S_r^{\ 3}$$

$$k_{r,g} = \left(1 - S_r\right)^3$$

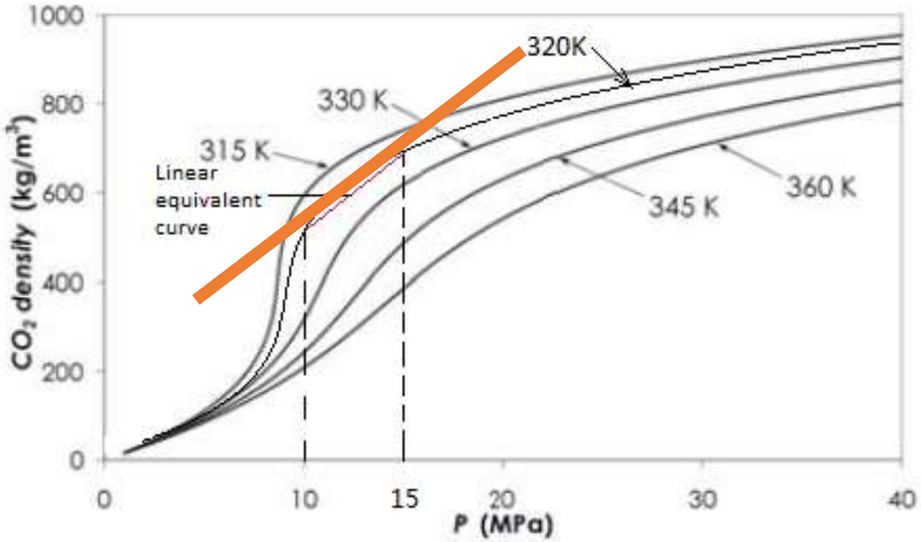
$k_{r,g}$-S_r



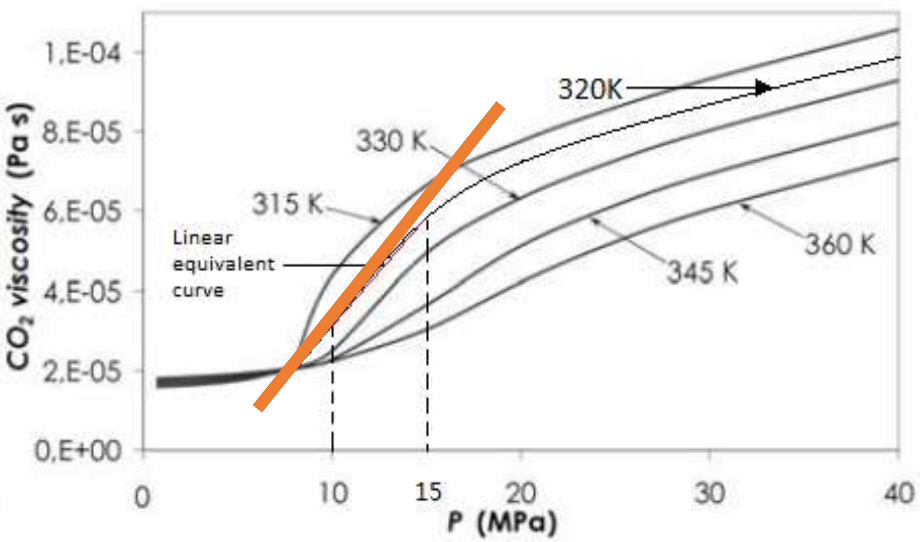
Hydro-mechanical model

- **Hydraulic properties**
  - ρ_{CO_2} & μ_{CO_2}

ρ_{CO_2}=f(P)



μ_{CO_2}=f(P)



$$\rho_{CO_2} = f\left(P,T\right), \mu_{CO_2} = f\left(P,T\right) \xrightarrow{\textbf{T=320K}} \rho_{CO_2} = f\left(P\right), \mu_{CO_2} = f\left(P\right)$$

Aquifer depth: 1.0km-1.5km ➔ **Pressure**: 10MPa-15MPa

Linearization:

$$\rho_{CO_2} = \rho_{CO_2,0} + \beta_1(P_g - P_{g,0}) \quad \& \quad \mu_{CO_2} = \mu_{CO_2,0} + \beta_2(P_g - P_{g,0})$$

Hydro-mechanical model

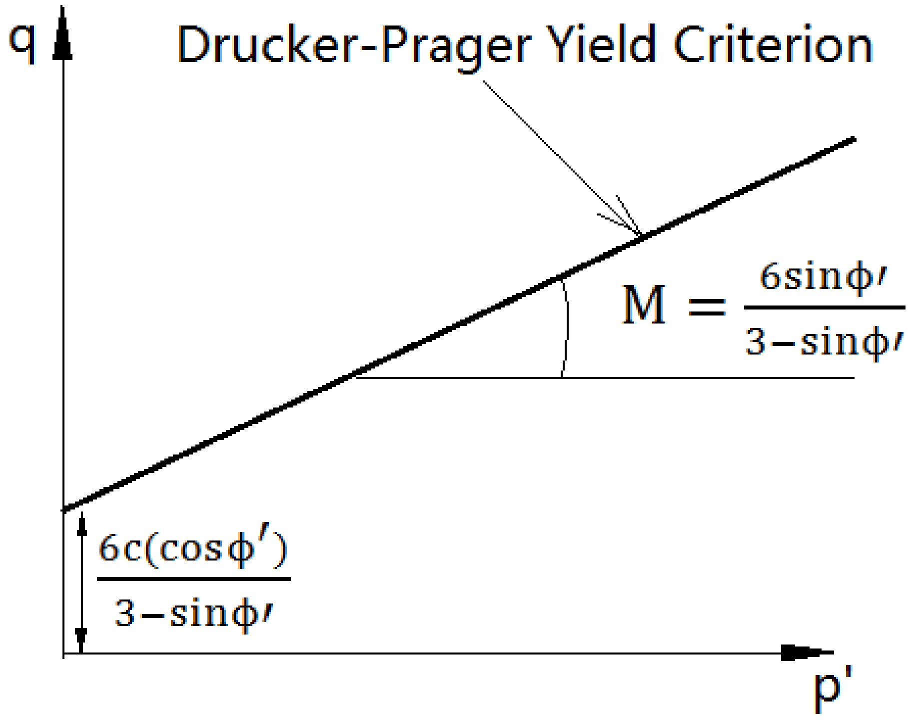
- **Elastoplastic model**

  - **Drucker-Prager** yield function

$$F \equiv q - Mp' - c\beta = 0$$

where

- c is the **cohesion**
- ϕ' is the **internal friction angle**



- **Bishop effective stress**

$$\sigma' = \sigma - \left(S_r P_w + (1 - S_r) P_g \right)$$

↓

Bishop pore pressure P_{pore}

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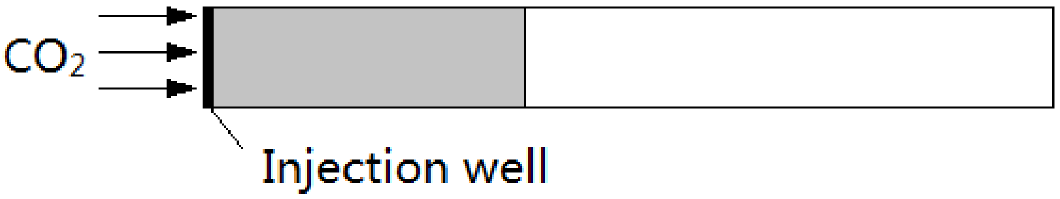
Numerical models

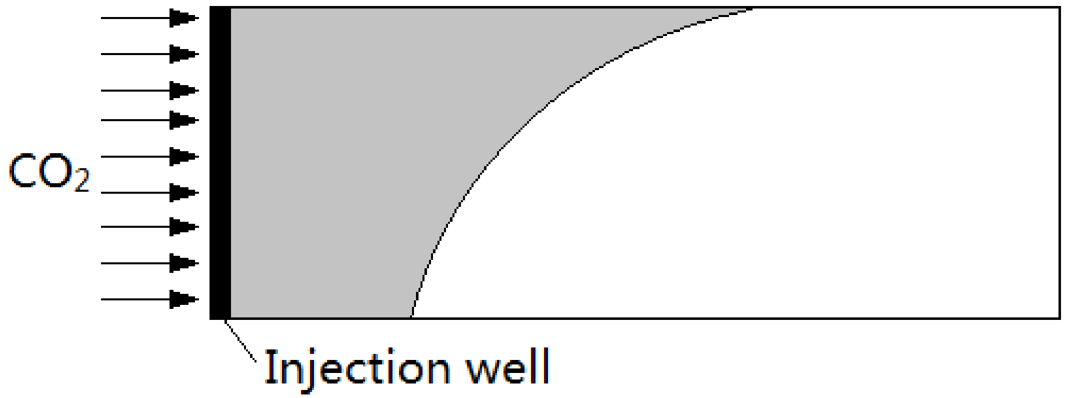
➢ **Modeling works in thesis**

Numerical simulations

- **1D model** (No gravity)
  - Hydraulic model (**H Model**)
    CO_2 lateral migration
  - Hydro-mechanical model (**HM Model**)
    HM coupling effects
- **2D model** (Gravity)
  - Hydraulic model (**H Model**)
    CO_2 buoyancy effects ($\rho_{CO_2} < \rho_w$)



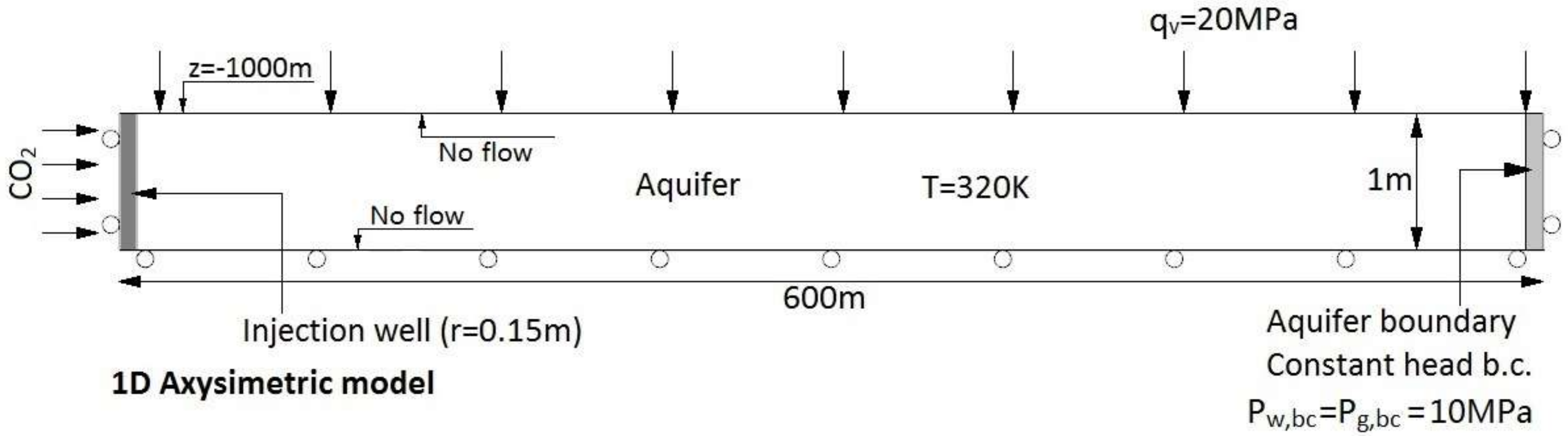
1D model



2D model

Numerical models (1D)

- **Geometry**



1D Axysimetric model

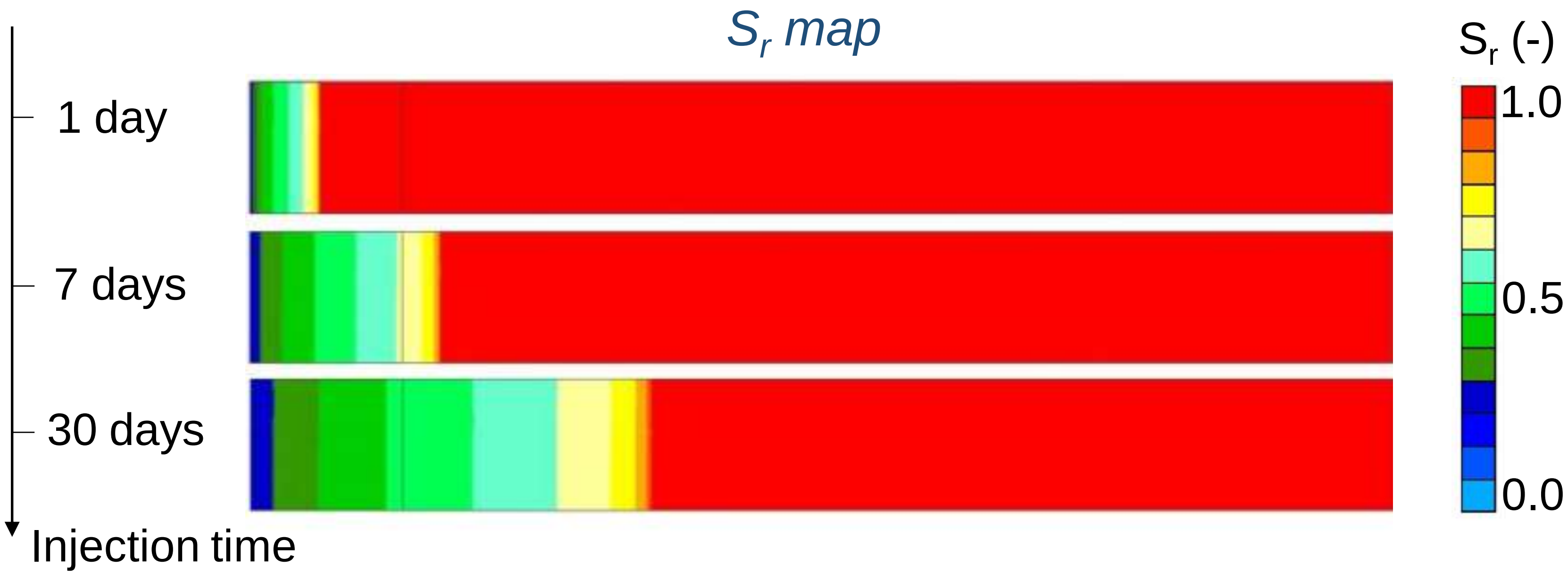
- **Boundary condition**
  - **Hydraulic BC**
    - F_{CO2}=2kg/s (*average rate of world famous projects*)
    - Outer boundary: $P_{g,bc} = P_{w,bc} = 10\text{MPa}$
    - Top&Bottom: No flow.
  - **Mechanical BC**
    - Well wall& outer boundary: u_x=0
    - Bottom:u_y=0
    - Top: q_v=20MPa

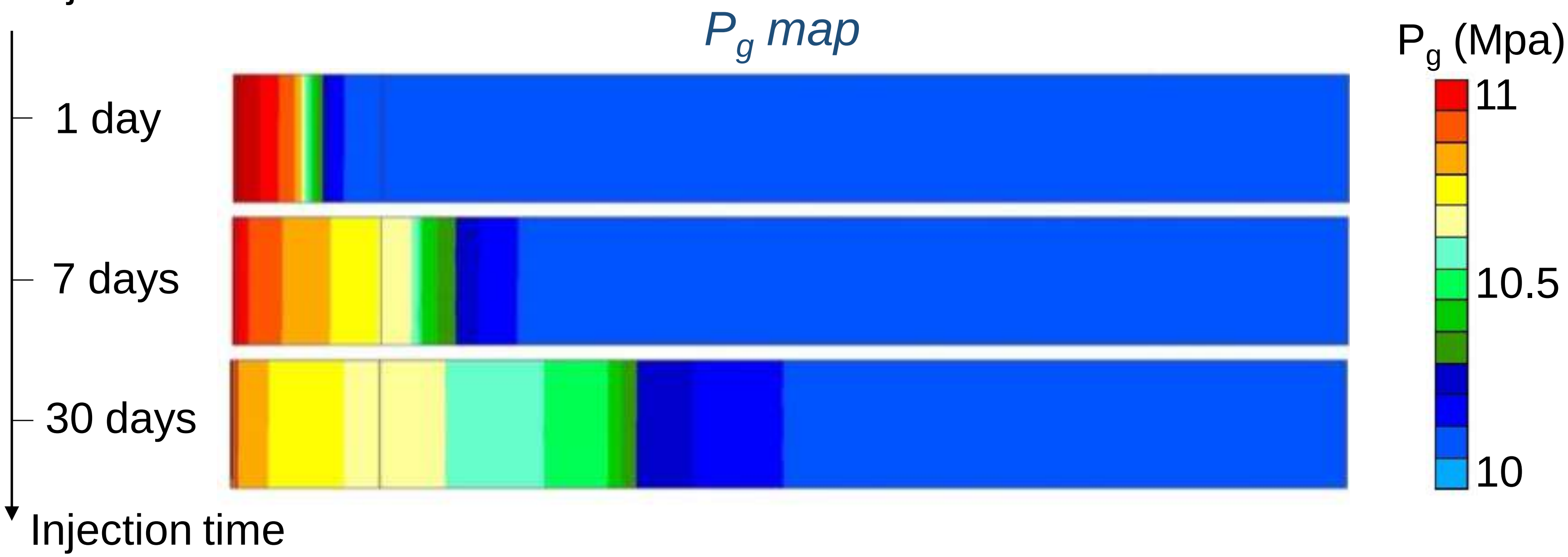
- **Initial condition**
  - $P_{g,0} = P_{w,0} = 10\text{MPa}$ & $T_0 = 320\text{K}$ (47℃)

- **Aquifer properties**
  - K_0=0.65, **Region compression**
  - k_{int}, c', ϕ, etc. Similar with **sandstone**

Numerical models (1D)

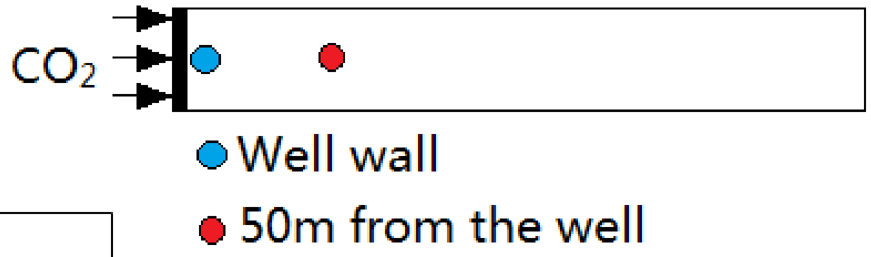
- **H Modeling**



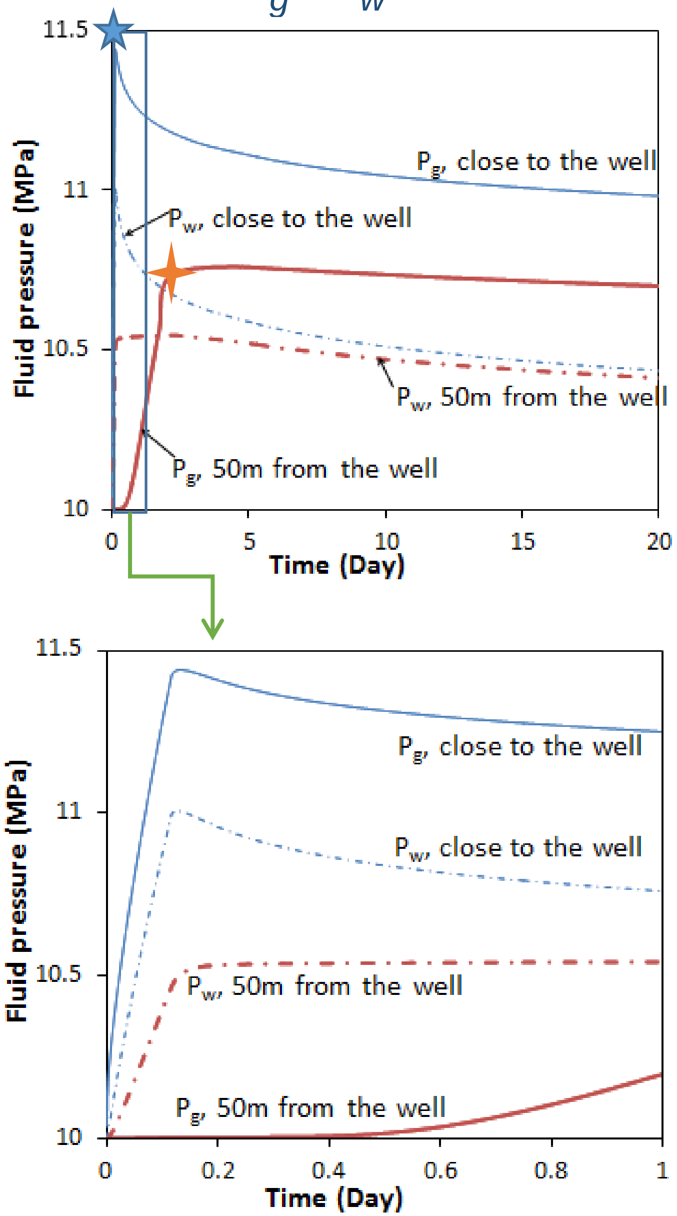


Numerical models (1D)

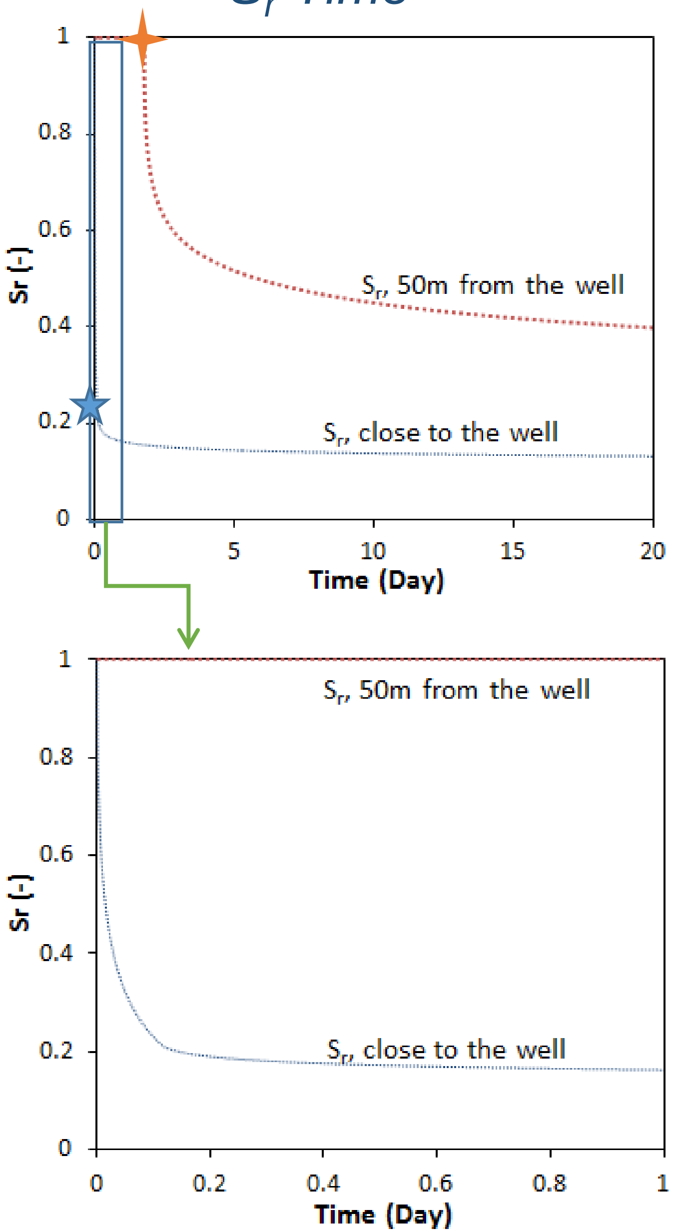
➢ **H Modeling**



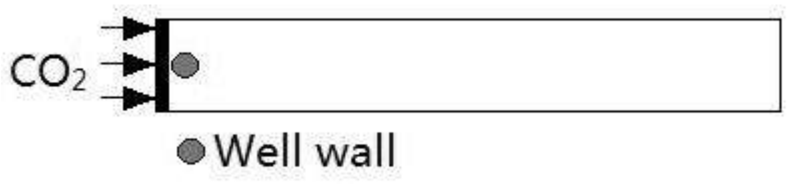
P_g&P_w-Time



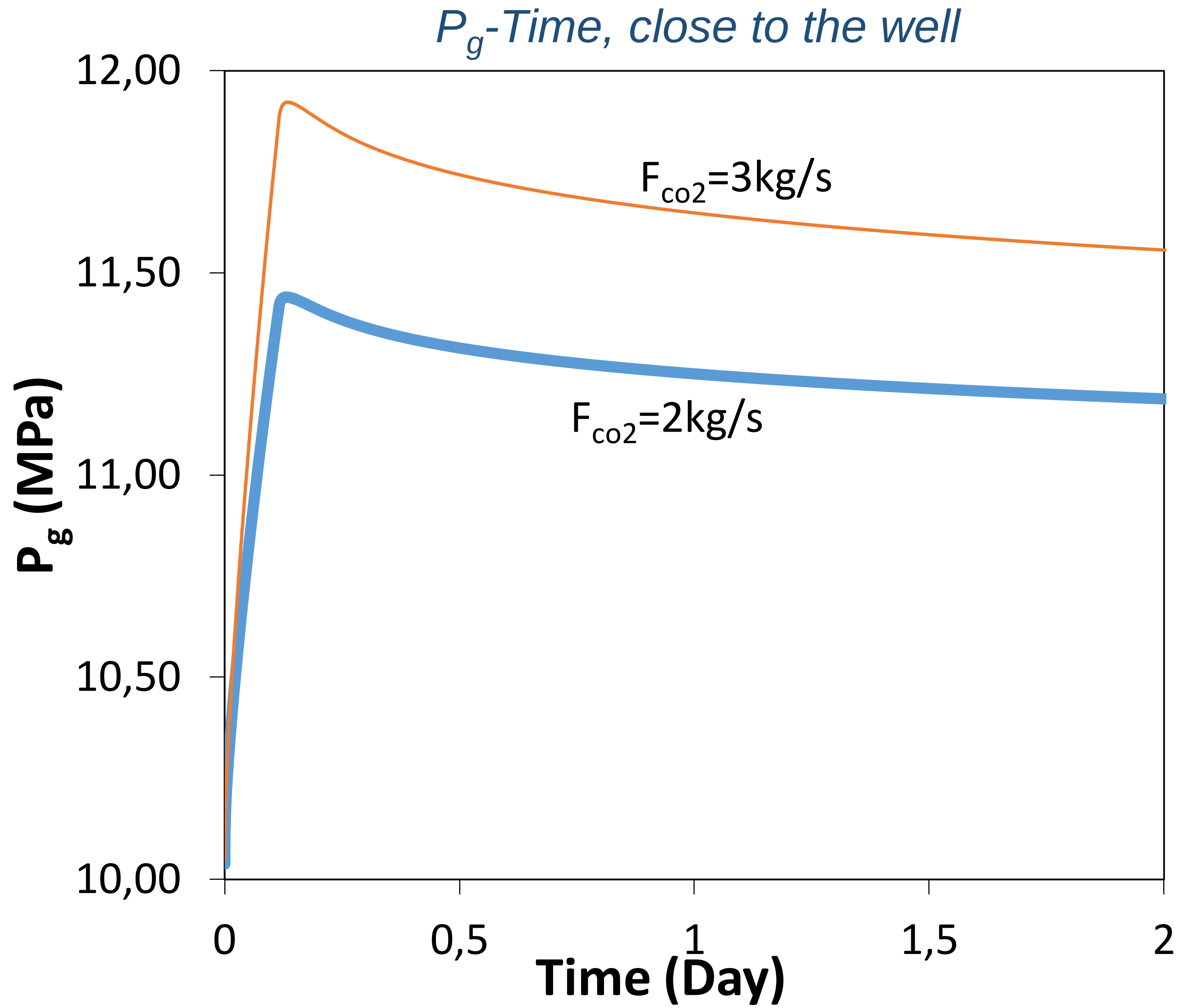
S_r-Time



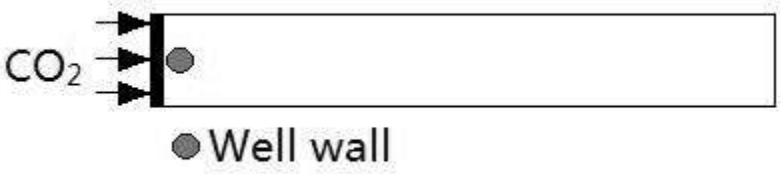
Numerical models (1D)



- **H Modeling**
- Sensitivity study – **Injection rate**

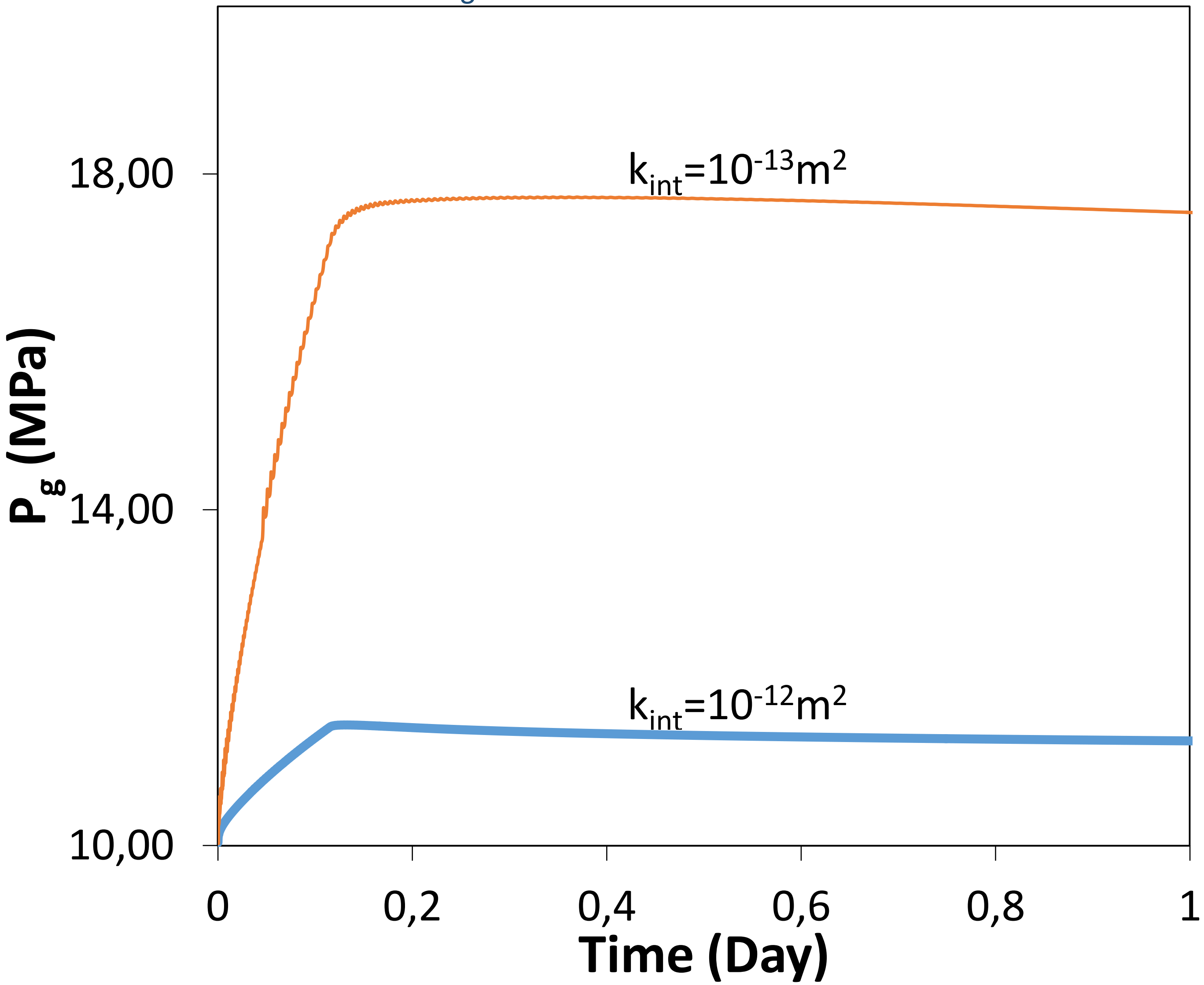


Numerical models (1D)



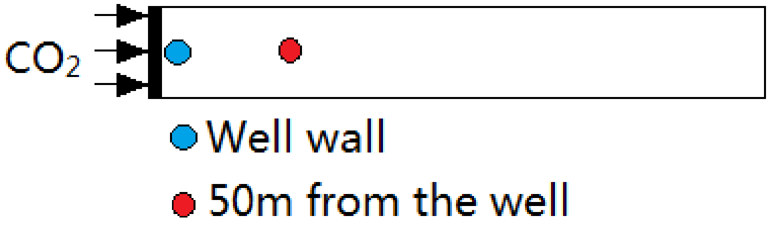
- **H Modeling**
- Sensitivity study – **Intrinsic permeability**

P_g-Time, close to the well

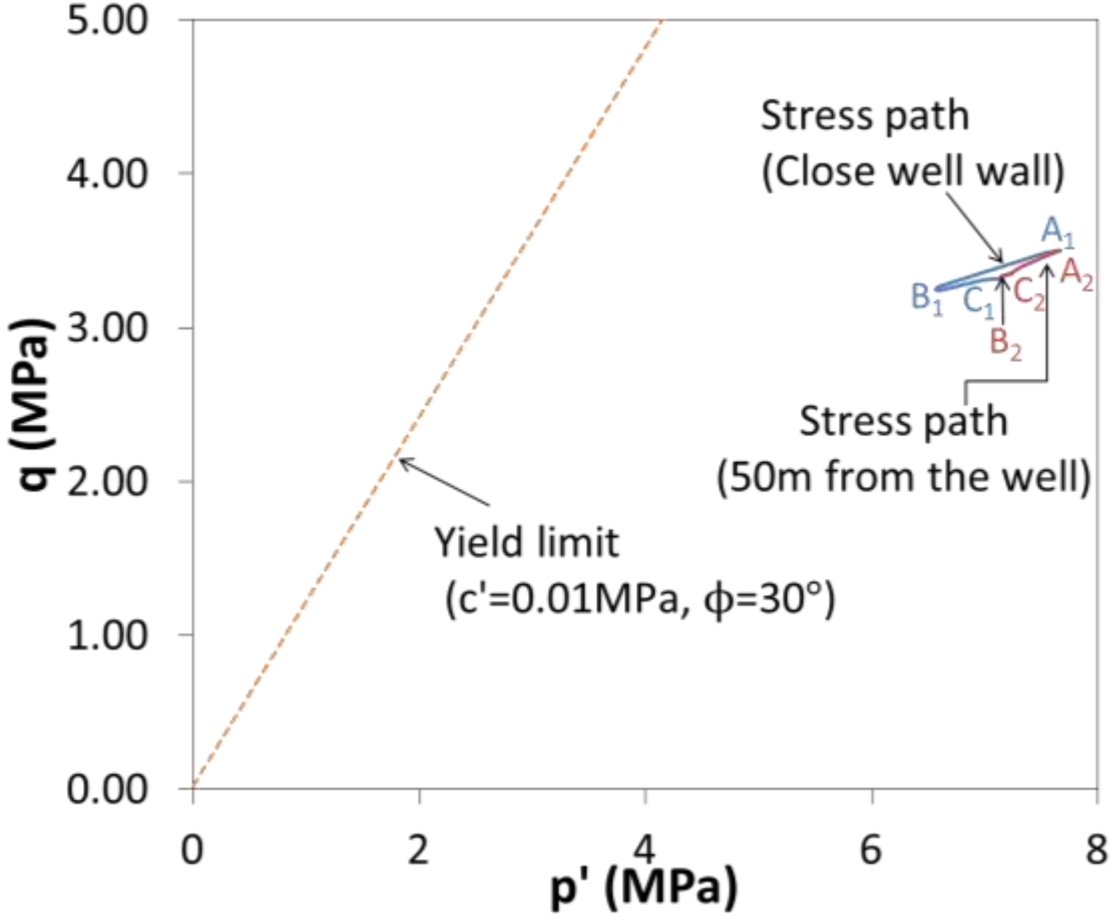


Numerical models (1D)

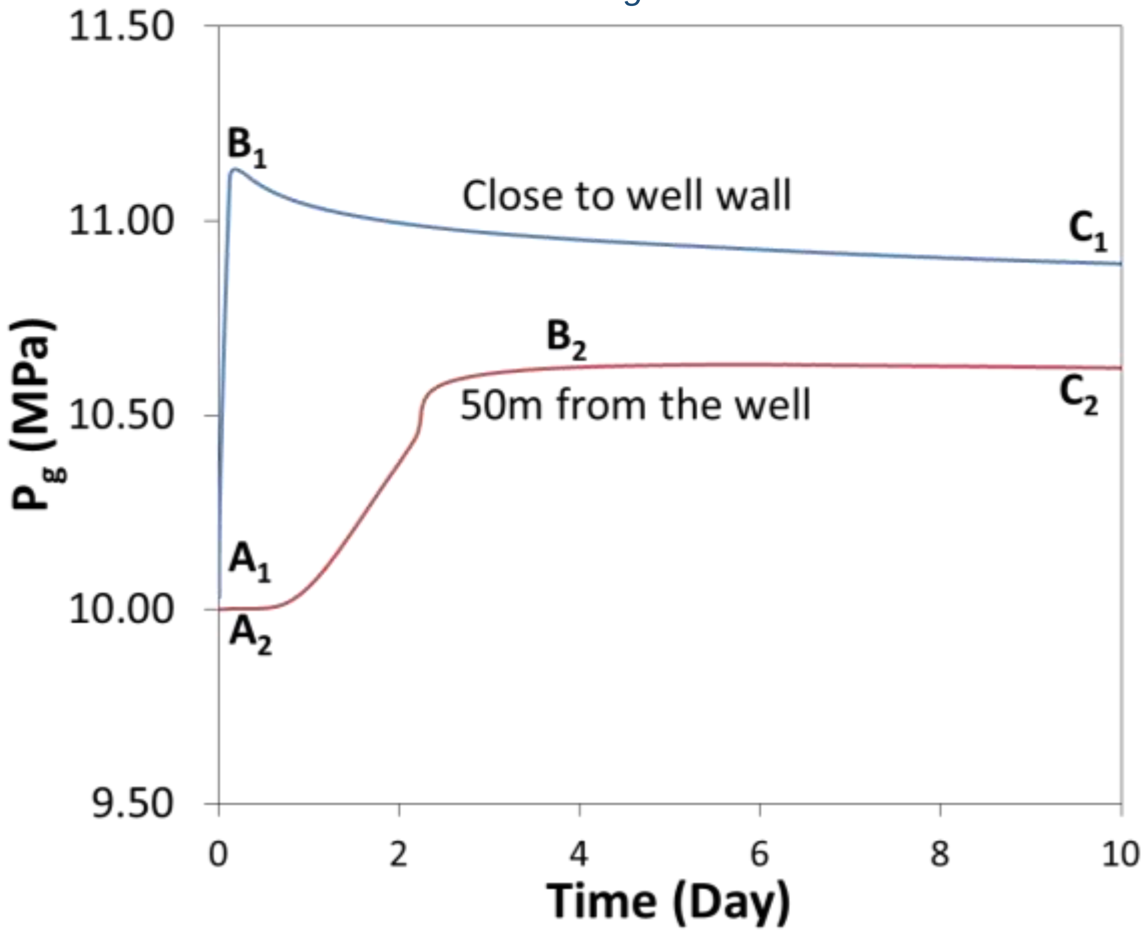
➢ **HM Modeling**



Stress paths (p', q) for 1 year



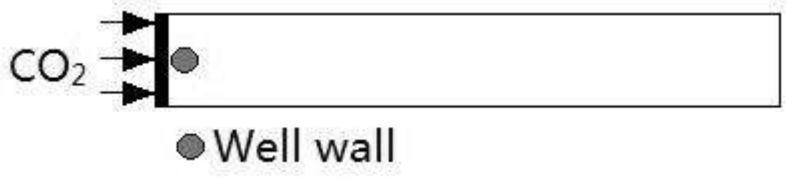
P_g-Time



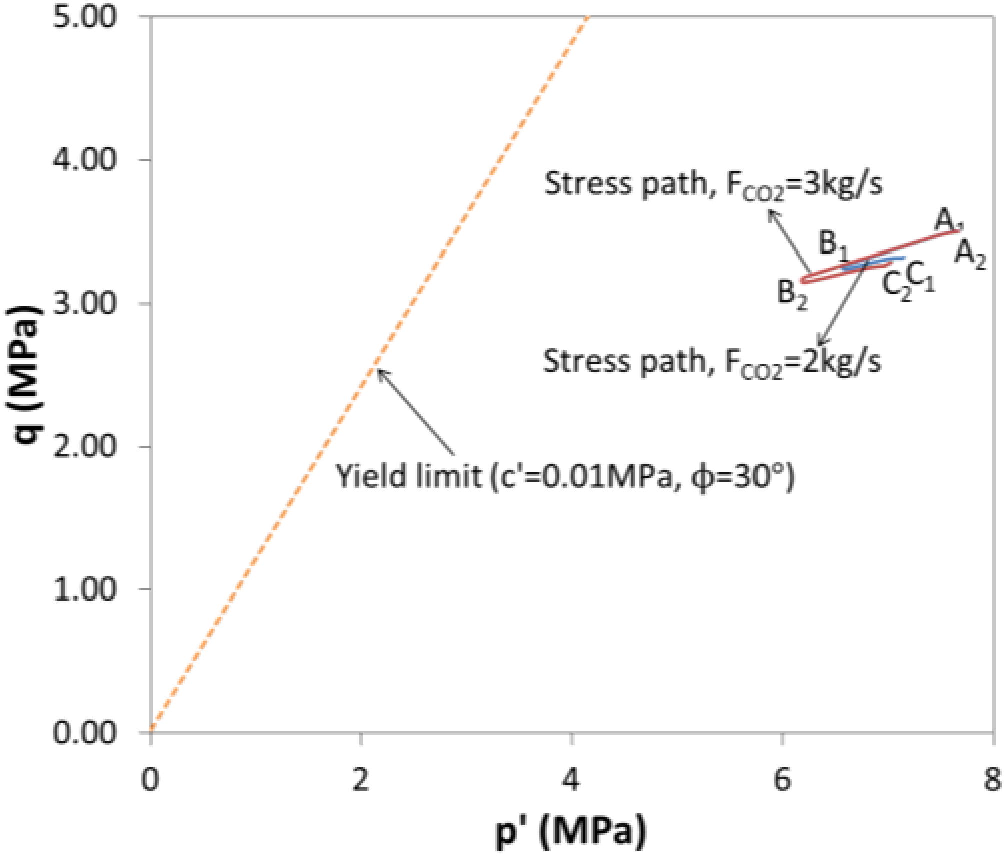
Numerical models (1D)

➢ **HM Modeling**

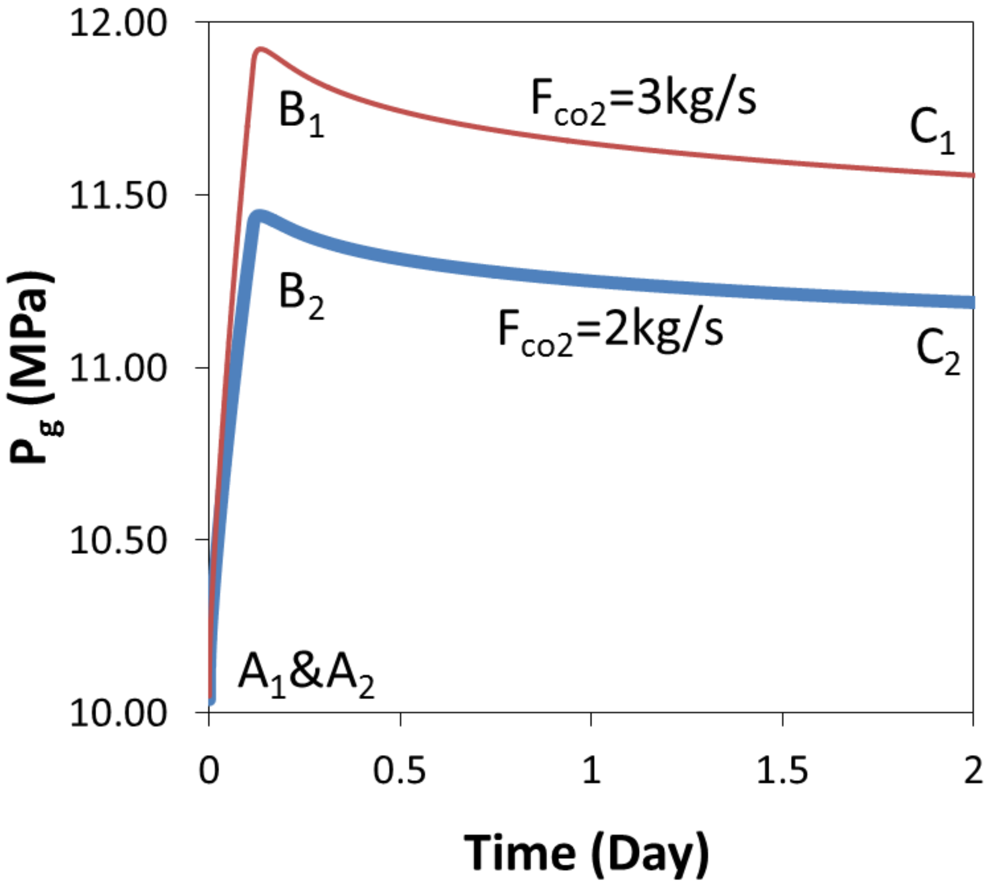
- Sensitivity study- **Injection rate**



Stress paths (p', q)

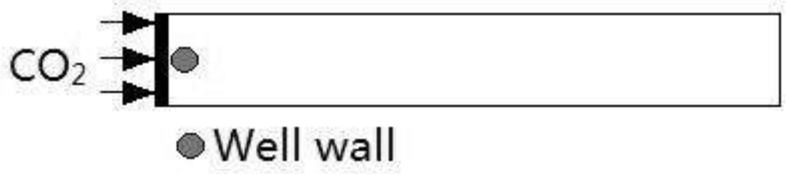


P_g-Time



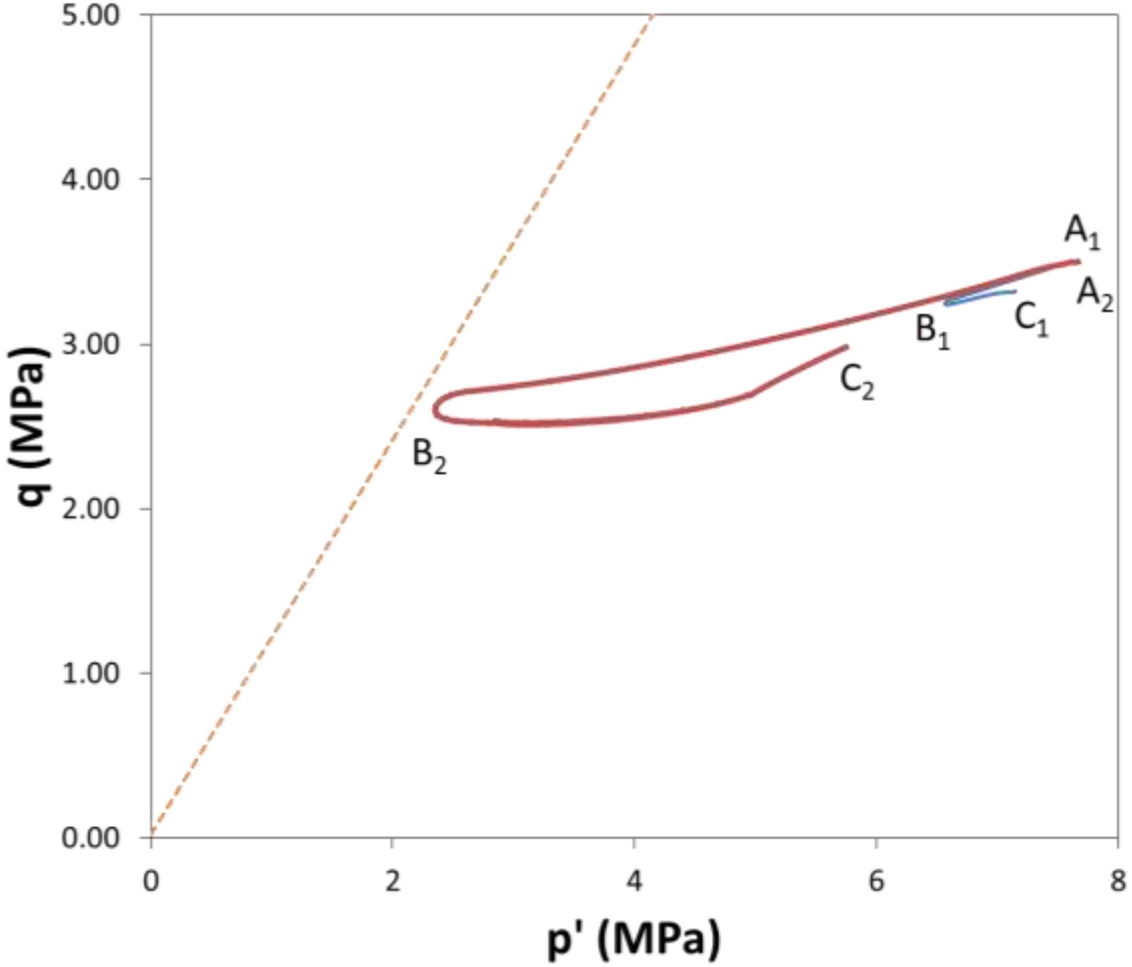
➔2kg/s → 3kg/s, closer to yield limit.

Numerical models (1D)



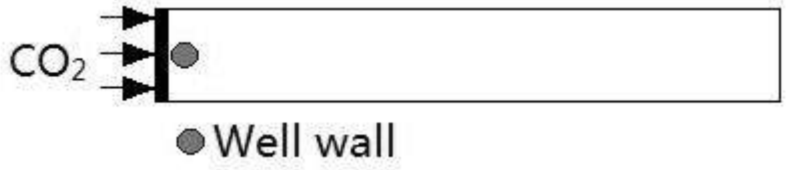
- **HM Modeling**
  - Sensitivity study- **Injection rate**

Stress paths (p', q)



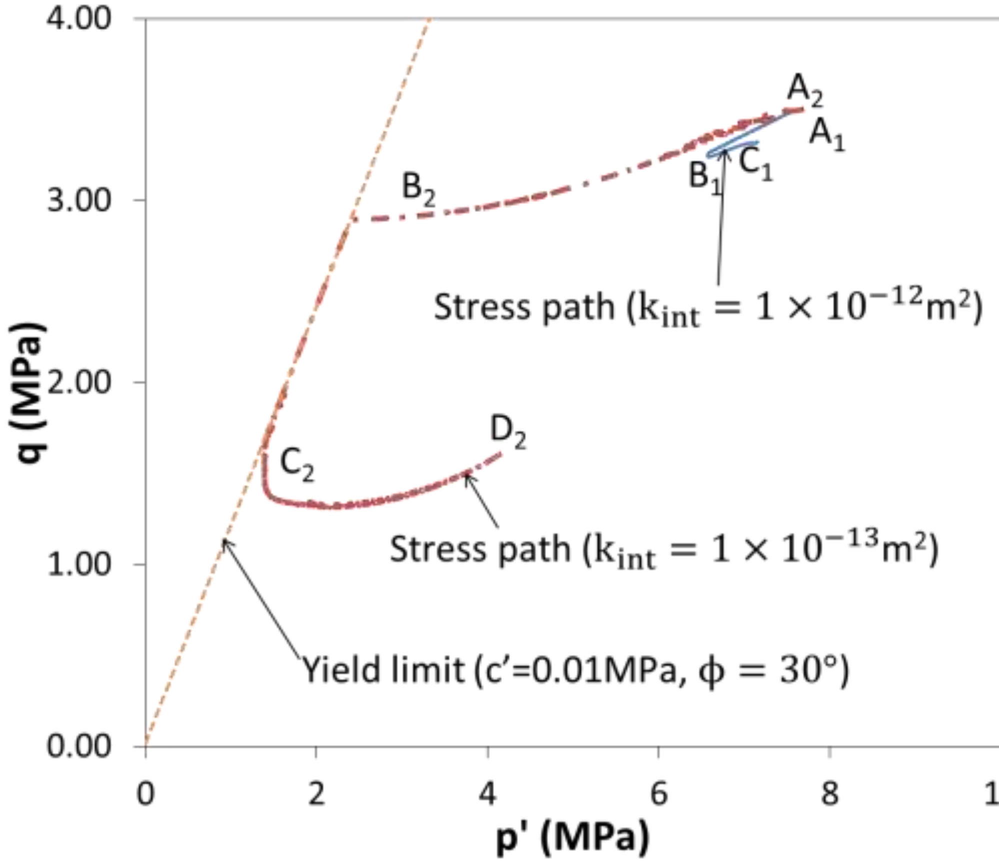
➔2kg/s → 17kg/s, Reach the yield limit.

Numerical models (1D)

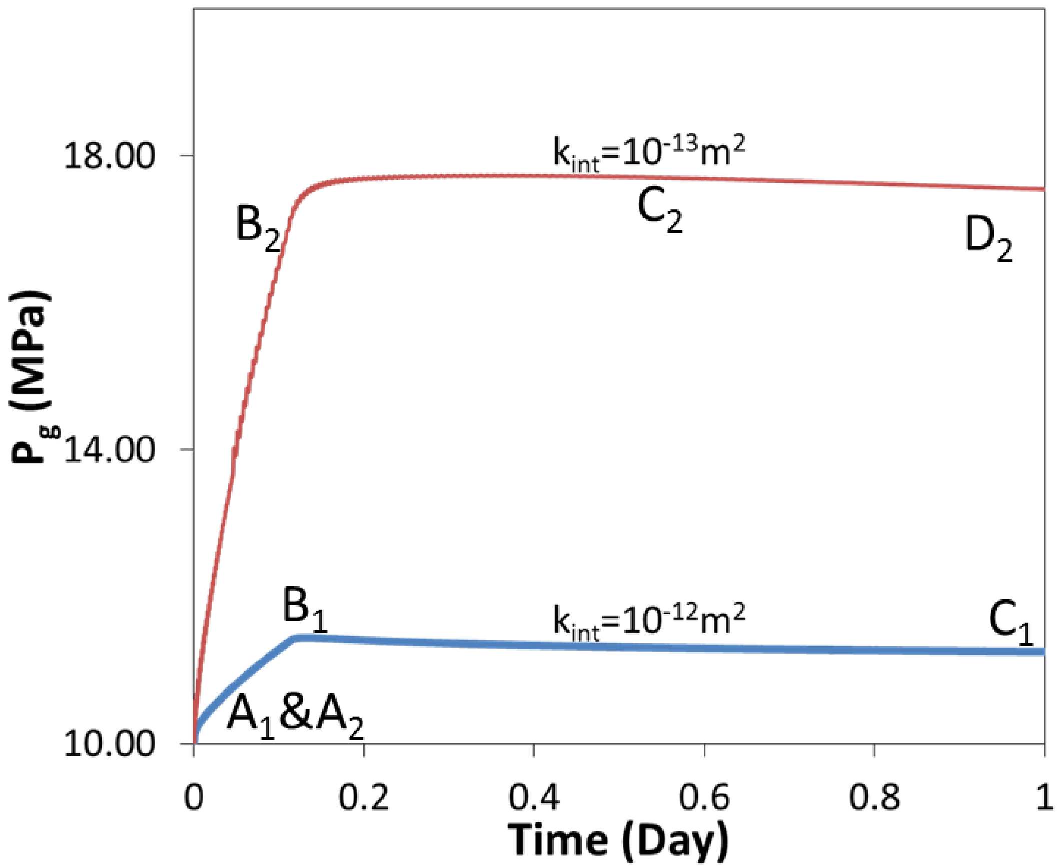


- **HM Modeling**
  - Sensitivity study- **Intrinsic permeability**

Stress paths (p', q)

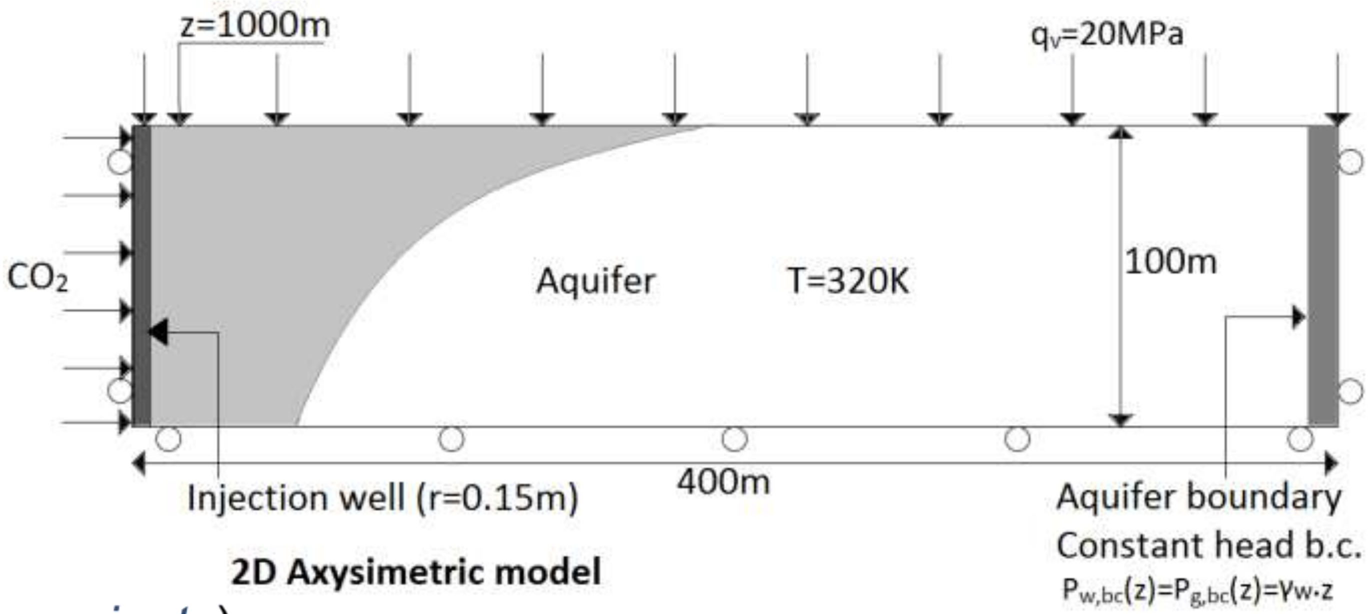


P_g-Time



➔Stress path ($k_{int}=1*10^{-13}m^2$), failure of reservoir.

Numerical models (2D)



- **Geometry**

- **Boundary Condition**

  - **Hydraulic BC**

    - F_{CO2}=2kg/s (*average rate of world famous projects*)
    - Outer boundary: $P_{g,bc} = P_{w,bc} = \gamma_w z$
    - Top&Bottom: No flow.

- **Initial condition**

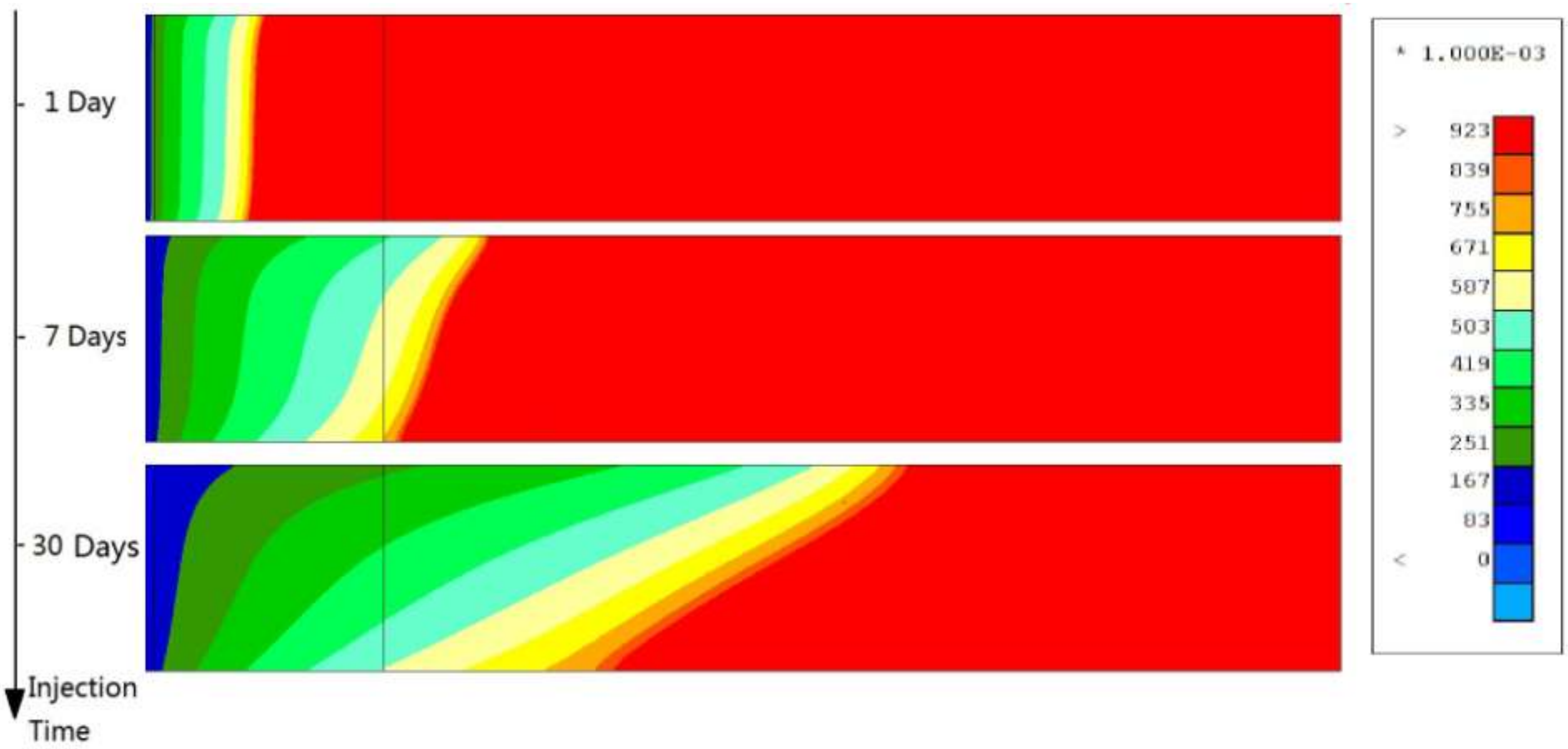
  - $P_{g,0} = P_{w,0} = \gamma_w z$ & $T_0 = 320K$ (47°C)

- **Aquifer properties**

  - K_0=0.65, Region in **compression**
  - E, c', ϕ, etc. Similar with **sandstone**

Numerical models (2D)

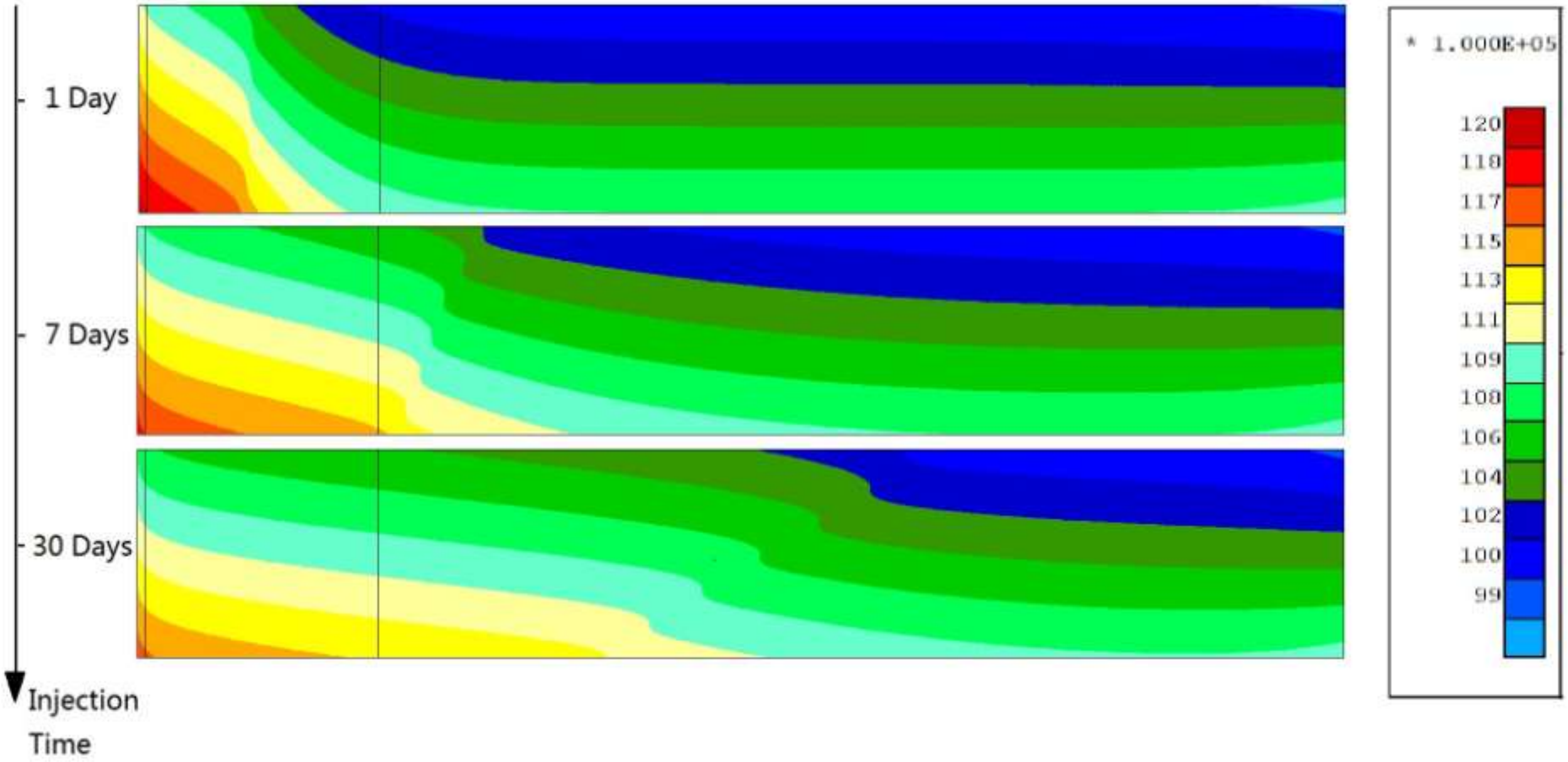
S_r map



- **Irregular** water-CO_2 interface
- **Non-uniform** S_r on vertical section

Numerical models (2D)

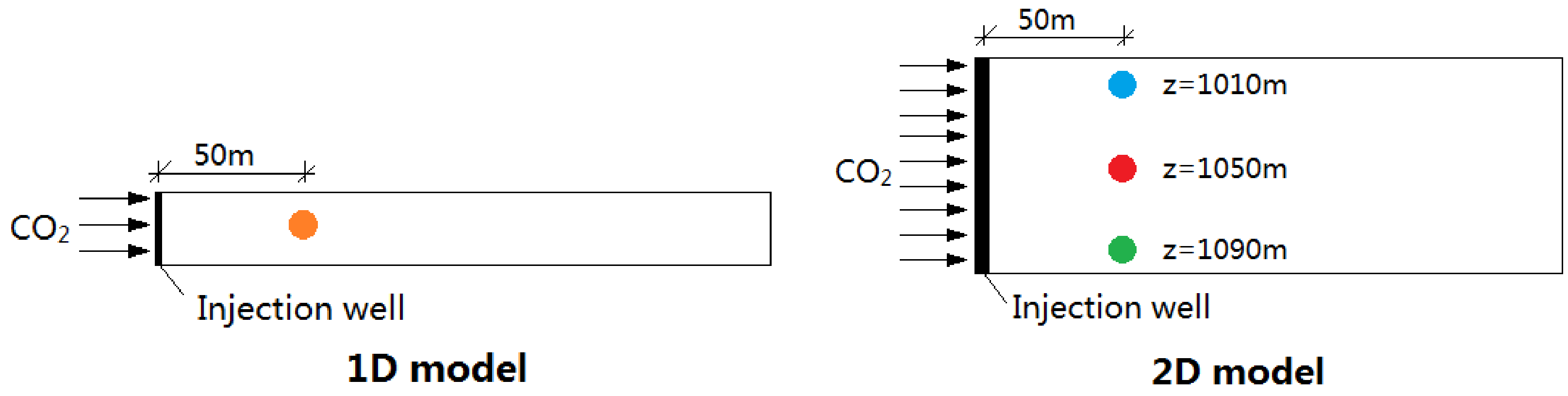
P_g map



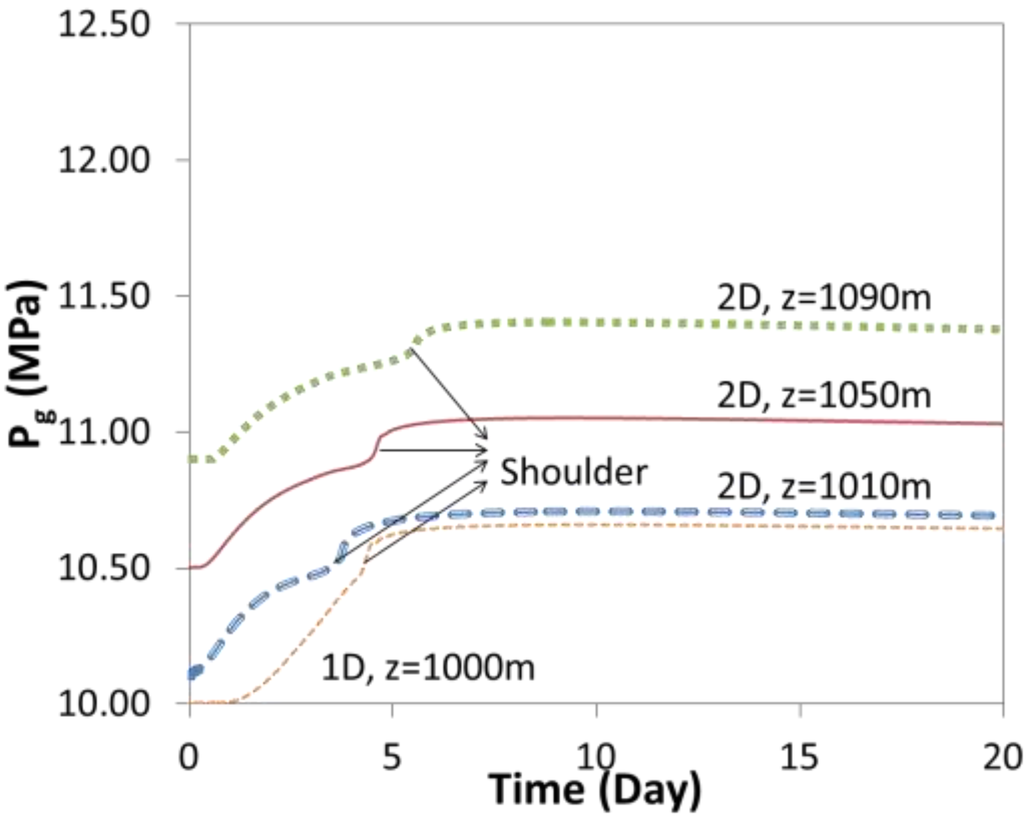
- **P_g gradient** in vertical direction
- **2D** P_g distribution

Numerical models (2D)

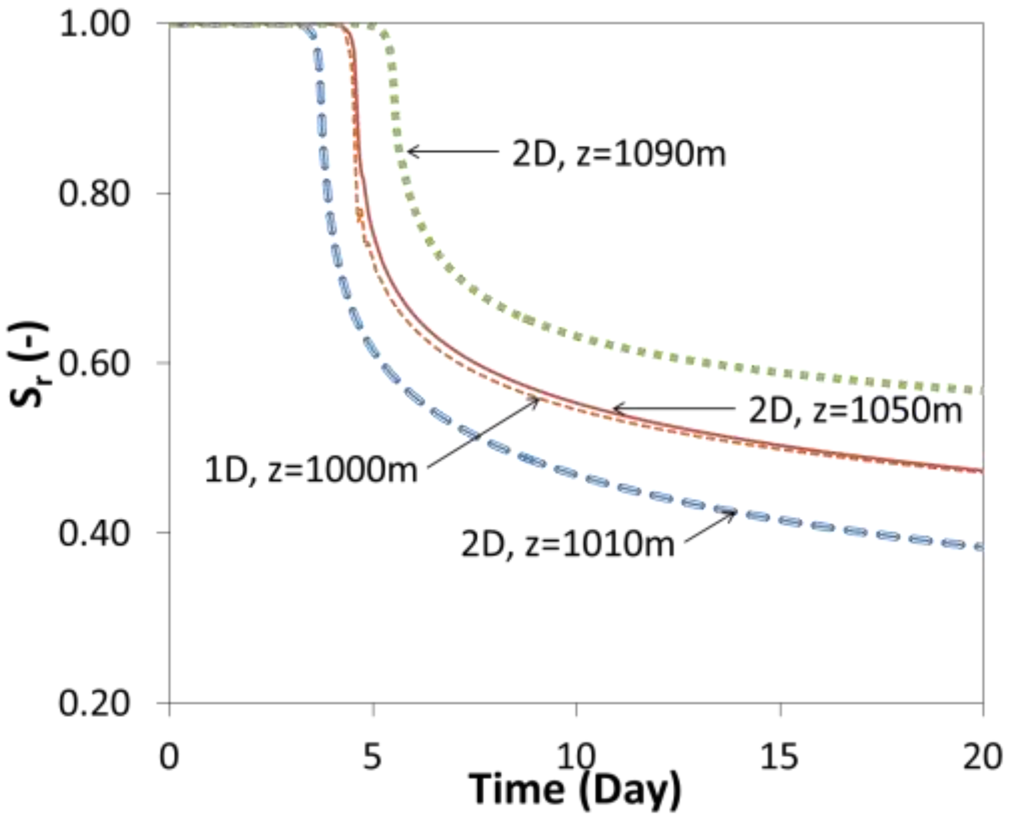
➢ **H Modeling**



P_g-Time, 50m from the well



S_r-Time, 50m from to the well



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Conclusion

- ΔP_g, ΔP_w, ΔS_r ➔ ΔP_{pore} ➔ $\Delta\sigma'$.
- **Injection** & **reservoir conditions** effects injection.
- Critical region: **close to the well**.
- Critical time: beginning of injection.
- **CO_2 buoyancy**

➔ ***Numerical modeling*** *is available to investigate the* ***CO_2 sequestration efficiency*** *&* ***reservoir stability****.*

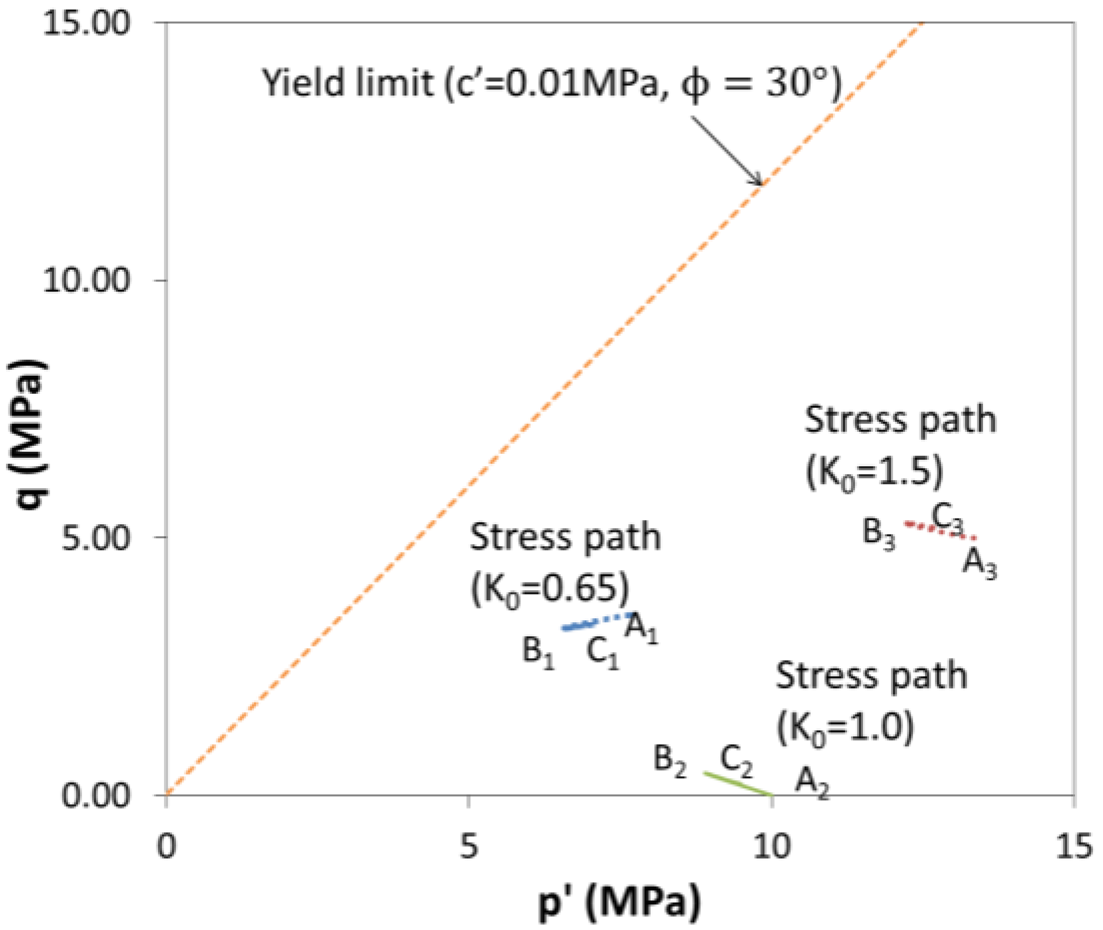
Perspectives

- Simulation of **aquifer-caprock system**
- **2D HM** modeling

Thanks for your attention!

Lateral earth pressure coefficient

Stress paths (p', q)



Initial stress states

	K_0=0.65	K_0=1.0	K_0=1.5
σ'_{x0} (MPa)	6.5	10.0	15.0
σ'_{y0} (MPa)	10.0	10.0	10.0
σ'_{z0} (MPa)	6.5	10.0	15.0
p'_0 (MPa)	7.7	10.0	13.3
q_0 (MPa)	3.5	0	5.00

- **Different** initial stress states.
- p' evolves in **same ways**.

Parameters of aquifer media

- The properties of aquifer media is similar with **sandstone media**

Property	Aquifer
Young's modulus, **E** (MPa)	1×10^4
Poisson's ratio, $\mathbf{\upsilon}$	0.3
Porosity, $\boldsymbol{\phi}$	0.1
Tortuosity, $\boldsymbol{\tau}$	0.25
Cohesion, $\mathbf{c'}$ (MPa)	0.01
Internal friction angle, $\boldsymbol{\phi'}$ (°)	30
Intrinsic permeability, $\mathbf{k_{int,g}}$ (m^2)	1×10^{-12}
Minimal relative permeability, $\mathbf{k_{r,min}}$ (-)	1×10^{-4}
Gas entry pressure, $\mathbf{P_r}$ (MPa)	0.2
Van Genuchten parameter, **n**	3
Lateral earth pressure coefficient, $\mathbf{K_0}$	0.65