CO_2 storage and injection modelling

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Agenda

- Background and motivation
- Summary on CO_2 storage/trapping mechanisms
- Model review: equations and physics
- Examples:
  1. Solubility trapping
  2. Residual trapping
  3. Poroelasticity
  4. Acidity (pH)

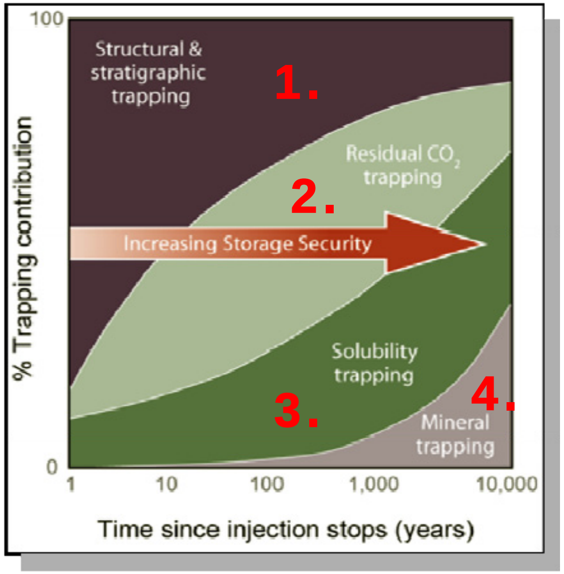
Background and motivation

Two main areas of interest (applications):

1. CO_2 Storage: focus on short term storage and the injection process
2. Shallow gas seepage: gas flow into and out of a well

CO_2 storage/trapping mechanisms

- Storage idea: Inject CO_2 into a **suitable** porous formation below an intact cap rock so that it will not **leak**
- Types of storage mechanisms of CO_2:
  1. Structural trapping: Migration blocked by impermeable cap rock layer(s)
  2. Residual trapping: CO_2 stabilized by capillary pressure
  3. Solubility trapping: In time CO_2 will dissolve in salt pore water (and descend)
  4. Mineral trapping: In time CO_2 will chemically react with rock to form carbonates and precipitate



(From: IPPC Special report, 2005)

Modelling challenges

1. How does the CO_2 migrate in/out of the formation, considering perforated/poorly plugged wells, faults, fractures, etc.
   - Two-phase flow (maybe even more phases)
2. How does CO_2 injection affect the rock
   - Poroelasticity (fracturing)
3. Chemical reactions and borehole integrity
   - Solubility of CO_2 in water (Other effects are: chemical reaction with rock formation (eg. calcite), corrosion, erosion, degradation of bore hole due to bad cement plugging)

Model review

Equations and physics

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Two-phase flow equations

$$\left.\begin{aligned}&\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha) - \nabla\cdot\left[\rho_\alpha\lambda_\alpha\mathbf{K}(\nabla p_\alpha + \gamma_\alpha\nabla z)\right] = \rho_\alpha q_\alpha\\&\sum S_\alpha = 1, \quad p_c = p_n - p_w, \quad S_{e\alpha} = f(p_c)\end{aligned}\right\}$$

General mass balances and auxiliary equations

$$\Downarrow$$

Do some equation manipulation: Eg. fractional flow formulation

(The fractional flow approach treats the multiphase flow problem as a total fluid flow of a single mixed fluid, and then describes the individual phases as fractions of the total flow)

Equations coming up!

Two-phase flow equations

$$\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha) - \nabla\cdot\left[\rho_\alpha\lambda_\alpha \mathbf{K}(\nabla p_\alpha + \gamma_\alpha \nabla z)\right] = \rho_\alpha q_\alpha$$

$$\sum S_\alpha = 1, \quad p_c = p_n - p_w, \quad S_{e\alpha} = f(p_c)$$

General mass balances and auxiliary equations

$$\Downarrow$$

$$\nabla\cdot\mathbf{u} = q_w + q_n - \frac{1}{\rho_w}\frac{\partial\rho_w}{\partial p}\left(\frac{\partial p}{\partial x}u_{w,x} + \frac{\partial p}{\partial y}u_{w,y} - \frac{\partial p}{\partial t}\phi S_w\right) - \frac{1}{\rho_n}\frac{\partial\rho_n}{\partial p}\left(\frac{\partial p}{\partial x}u_{n,x} + \frac{\partial p}{\partial y}u_{n,y} - \frac{\partial p}{\partial t}\phi S_n\right) - \frac{\partial\phi}{\partial t}$$

$$\phi\rho_w\frac{\partial S_w}{\partial t} + \nabla\cdot(\rho_w\mathbf{u}_w) = \rho_w q_w - \phi S_w\frac{\partial\rho_w}{\partial p}\frac{\partial p}{\partial t} - \rho_w S_w\frac{\partial\phi}{\partial t}$$

$$\mathbf{u} = -\mathbf{K}\left(\lambda\nabla p - (\lambda_w\rho_w + \lambda_n\rho_n)\mathbf{g}\right)$$

$$\mathbf{u}_w = f_w\mathbf{u} + \lambda_n f_w K\left(\nabla p_c + (\rho_w - \rho_n)\mathbf{g}\right)$$

$$\mathbf{u}_n = f_n\mathbf{u} - \lambda_n f_w K\left(\nabla p_c + (\rho_w - \rho_n)\mathbf{g}\right)$$

Biot linear poroelasticity equation

Two-ways coupling:

- Flow coupled to geomechanics:

$$\nabla \cdot [\boldsymbol{\sigma}] = -\mathbf{F} \qquad \boldsymbol{\sigma} = \mathbf{D}_{el}\boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0 - \alpha_{biot} p \mathbf{I}$$

- Geomechanics coupled to flow:

$$\phi^* = (1 - \varepsilon_v)\phi \qquad q_w = q_n = -\alpha_{biot} \frac{\partial \varepsilon_v}{\partial t} \qquad K = K_0 \left(\frac{\phi^*}{\phi} \right)^{20}$$

Mass balance equation, CO_2(aq)

$$\frac{\partial\left(\phi S_w C_{CO_2}\right)}{\partial t} + \nabla\cdot\left(-D_{CO_2}\phi S_w \nabla C_{CO_2}\right) = F$$

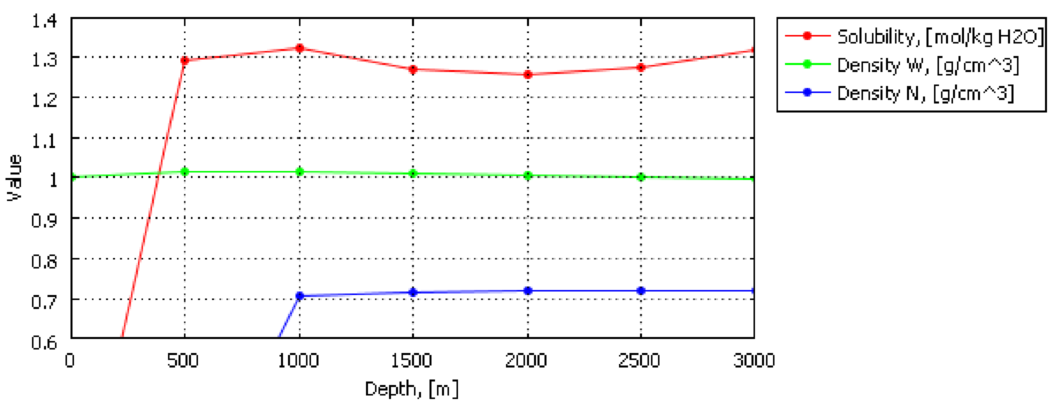
$$\frac{\partial C_{CO_2}}{\partial t} + \nabla\cdot\left(-D_{CO_2}\phi S_w \nabla C_{CO_2}\right) = F - \phi C_{CO_2}\frac{\partial S_w}{\partial t} - S_w C_{CO_2}\frac{\partial \phi}{\partial t}$$

$$F = k_s\left(min\left(C_{sat,CO_2} S_w, C_{0,CO_2} S_n\right) - C_{CO_2}\right)$$

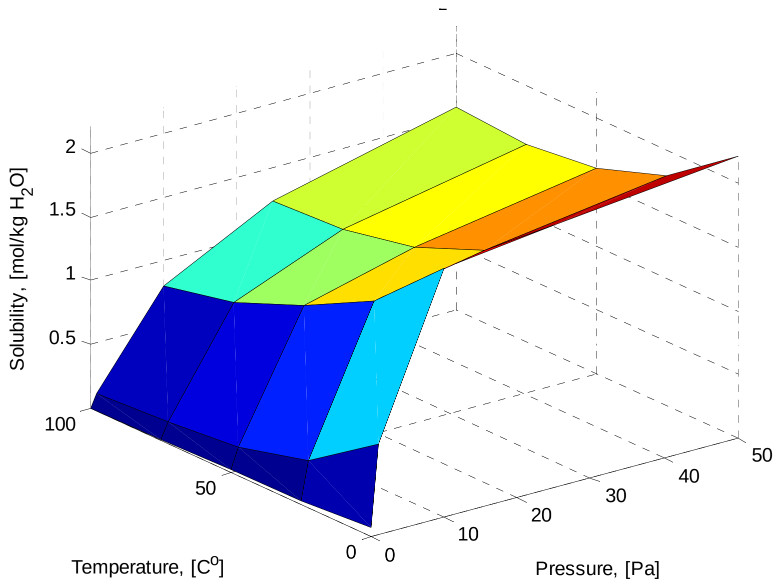
C_{CO2} – concentration of dissolved CO_2 in the wetting phase [mol/m³]
$C_{sat,CO2}$ – saturation concentration of CO_2 in water; CO_2(aq) [mol/m³]
$C_{0,CO2}$ – concentration of pure CO_2 [mol/m³]

CO_2 solubility and densities

Symbol	Value	Unit	Description
ρ_{H2O}	1000	[kg/m^3]	Density of water-phase
ρ_{CO2}	700	[kg/m^3]	Density of CO_2-phase
$C_{sat,CO2}$	1300	[mol/m^3]	Saturation concentration of CO_2(aq)



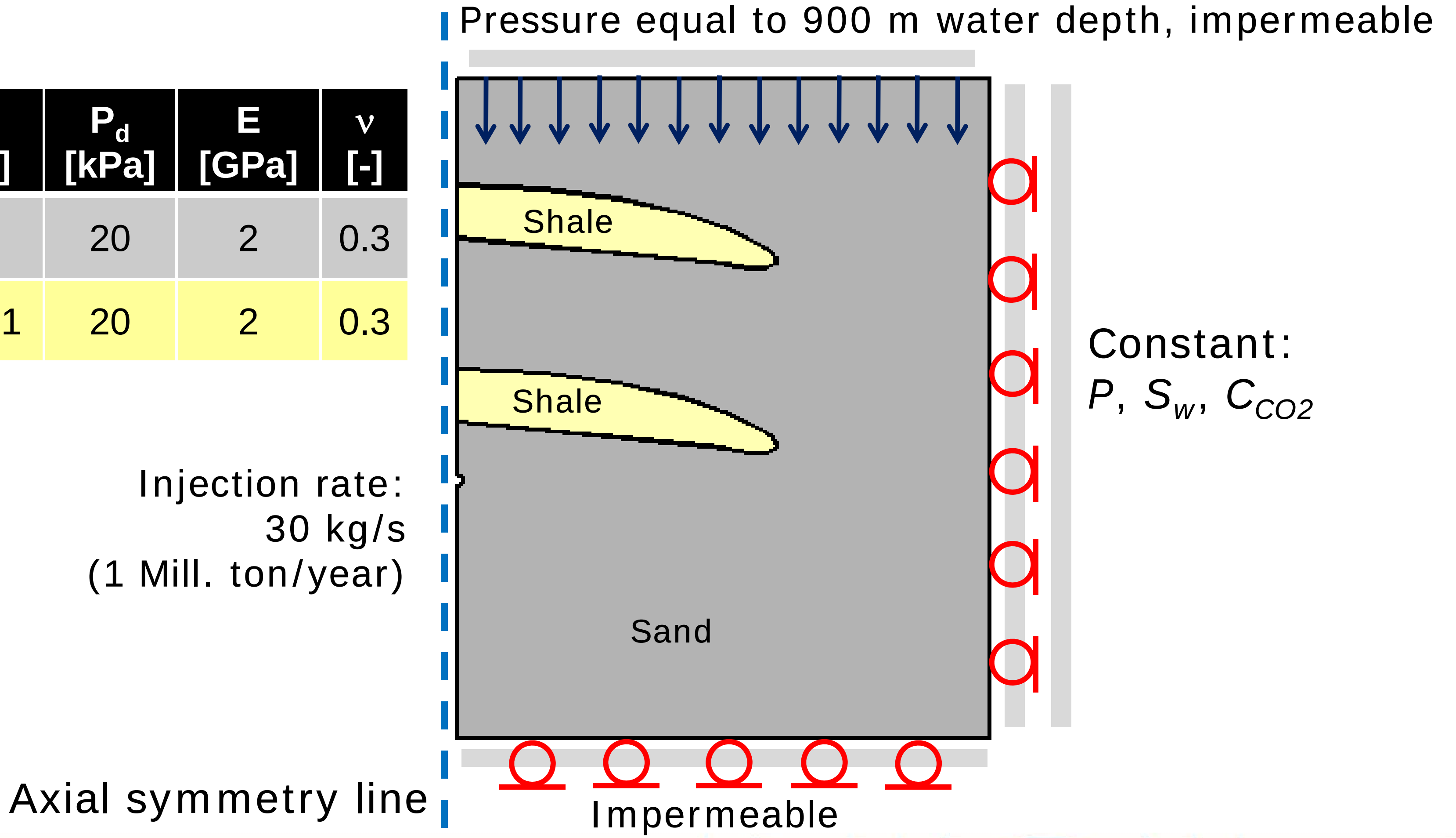
(Temperature gradient used: 28 °K/km)



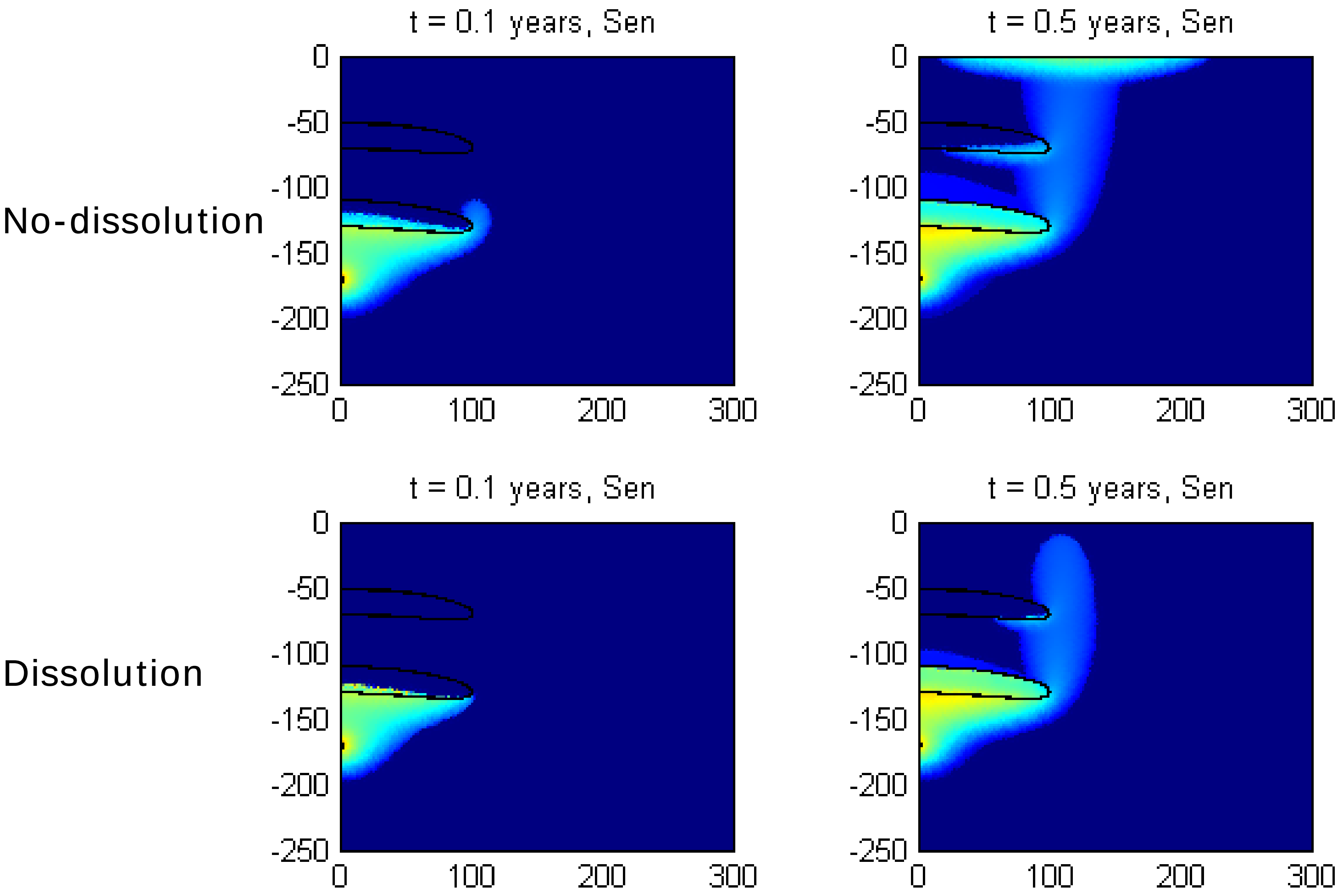
Model definition

Model (200 x 300 m^2), axial symmetry

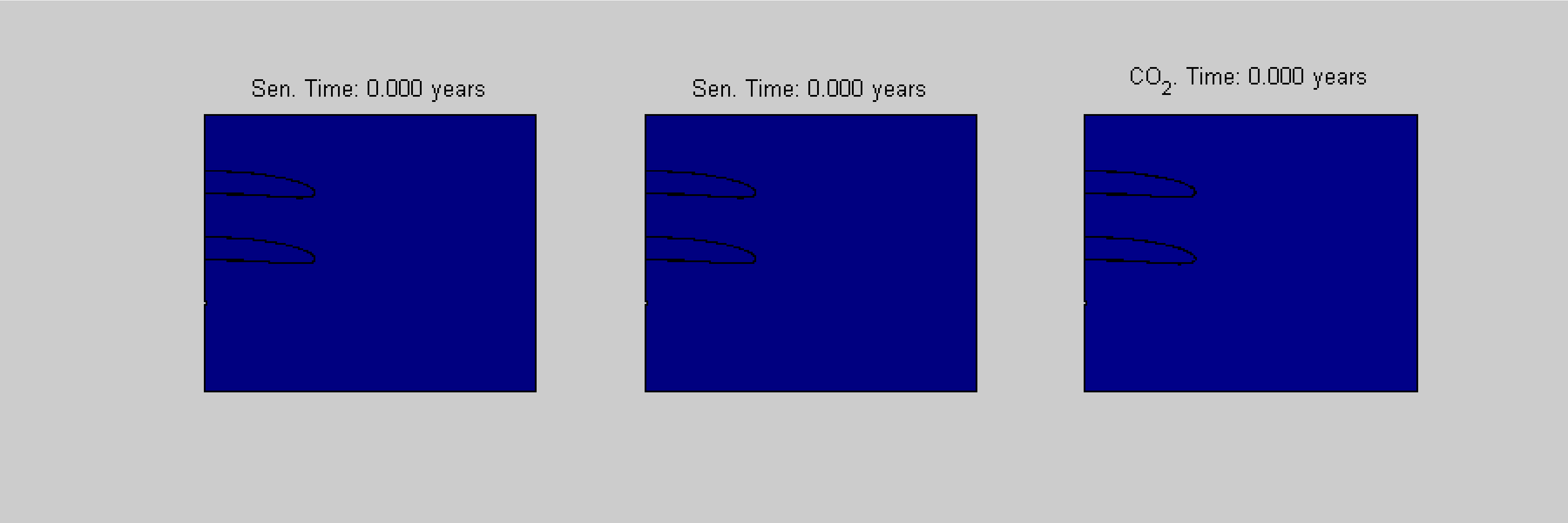
ϕ [-]	K [D]	P_d [kPa]	E [GPa]	ν [-]
0.4	3	20	2	0.3
0.1	0.01	20	2	0.3



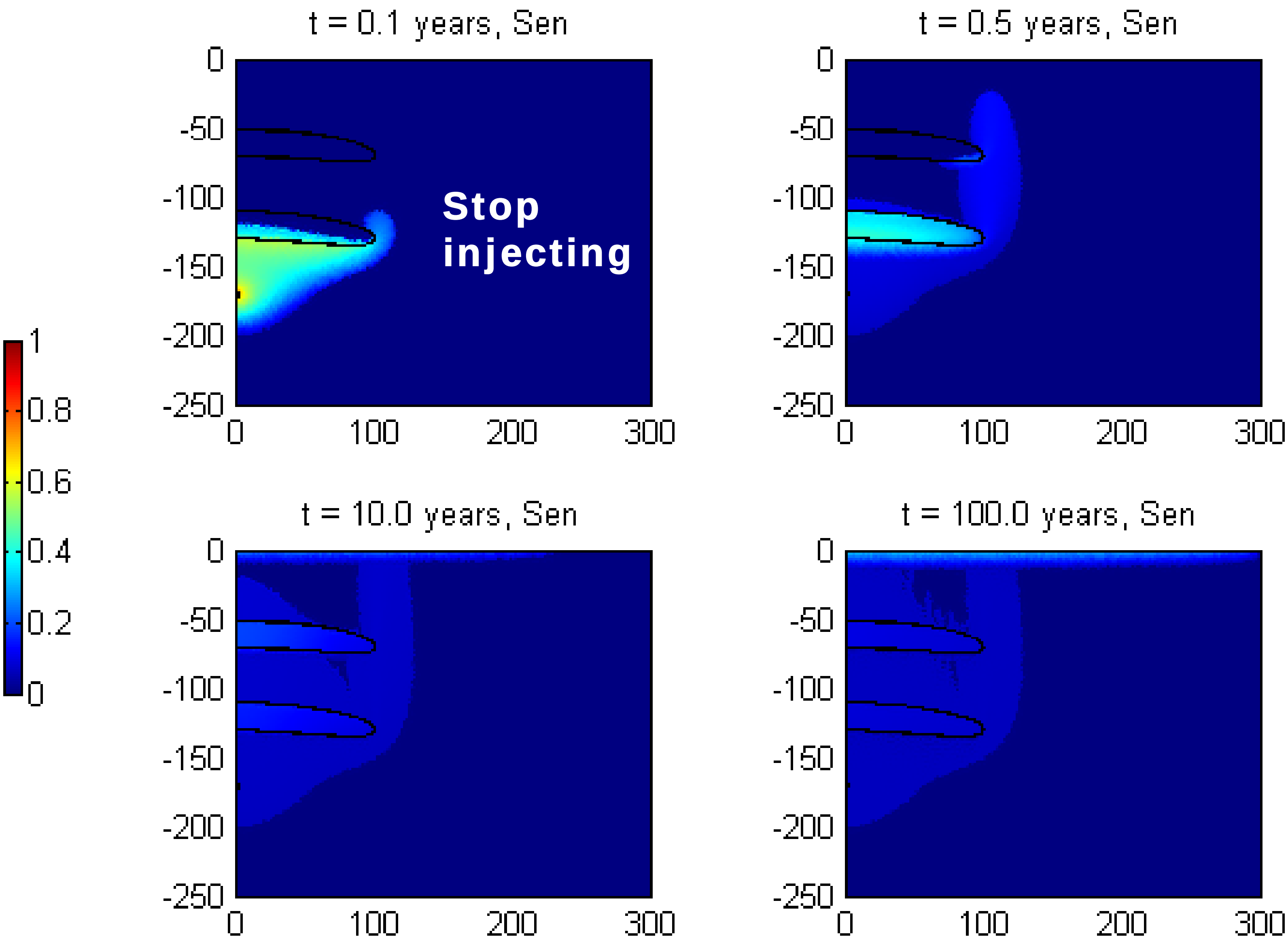
Examples



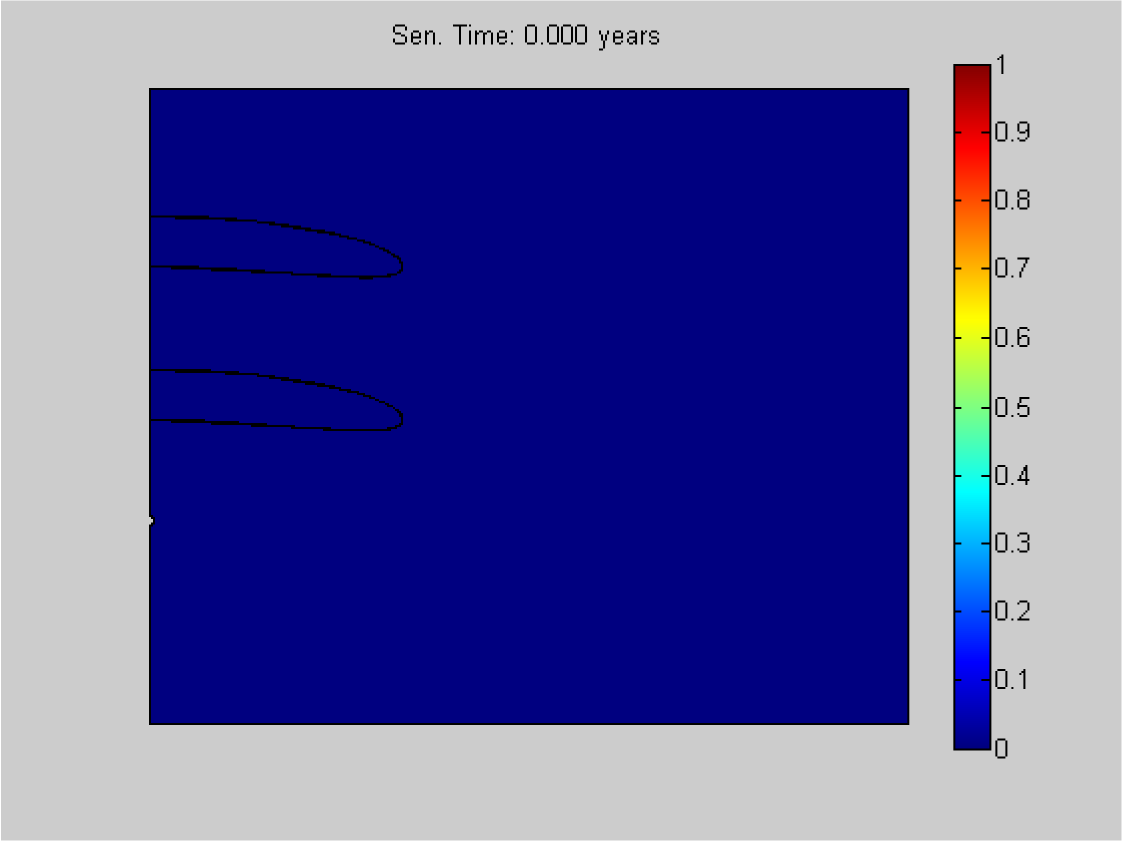
1: Solubility trapping



1: Solubility trapping

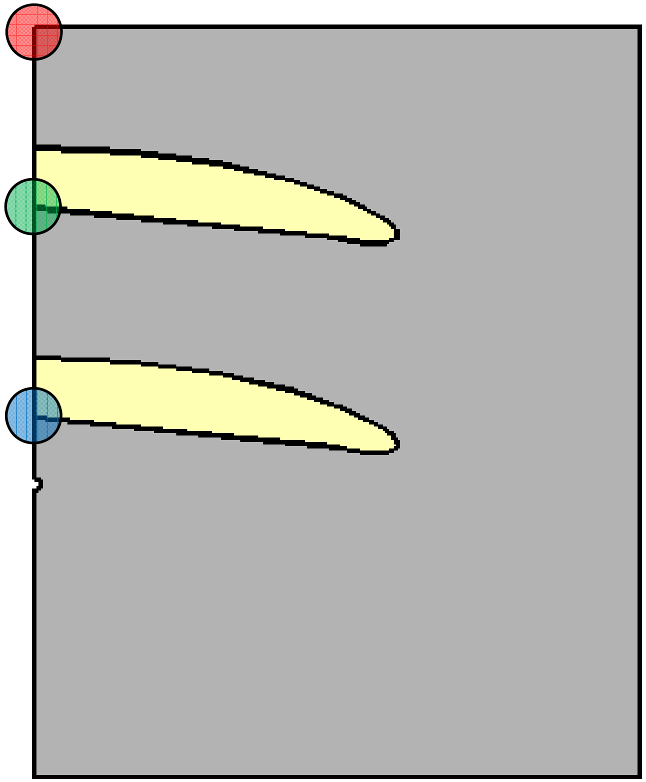


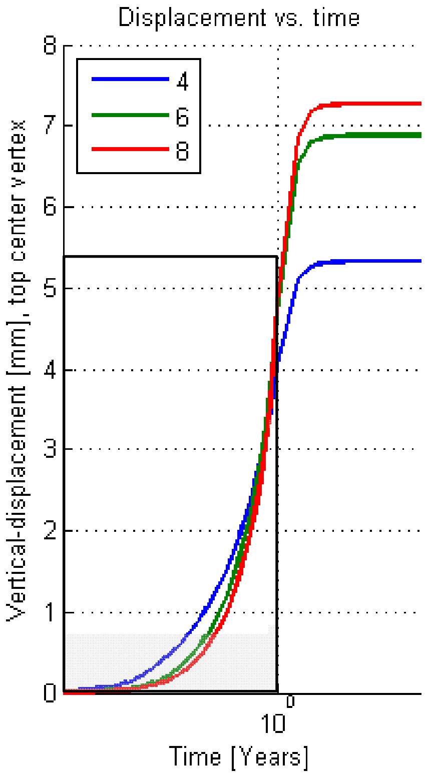
2: Residual trapping (S_r = 0.05)

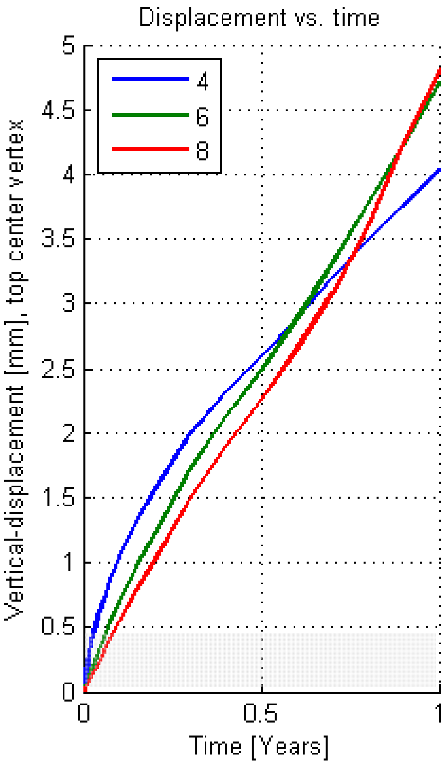


2: Residual trapping (S_r = 0.05)

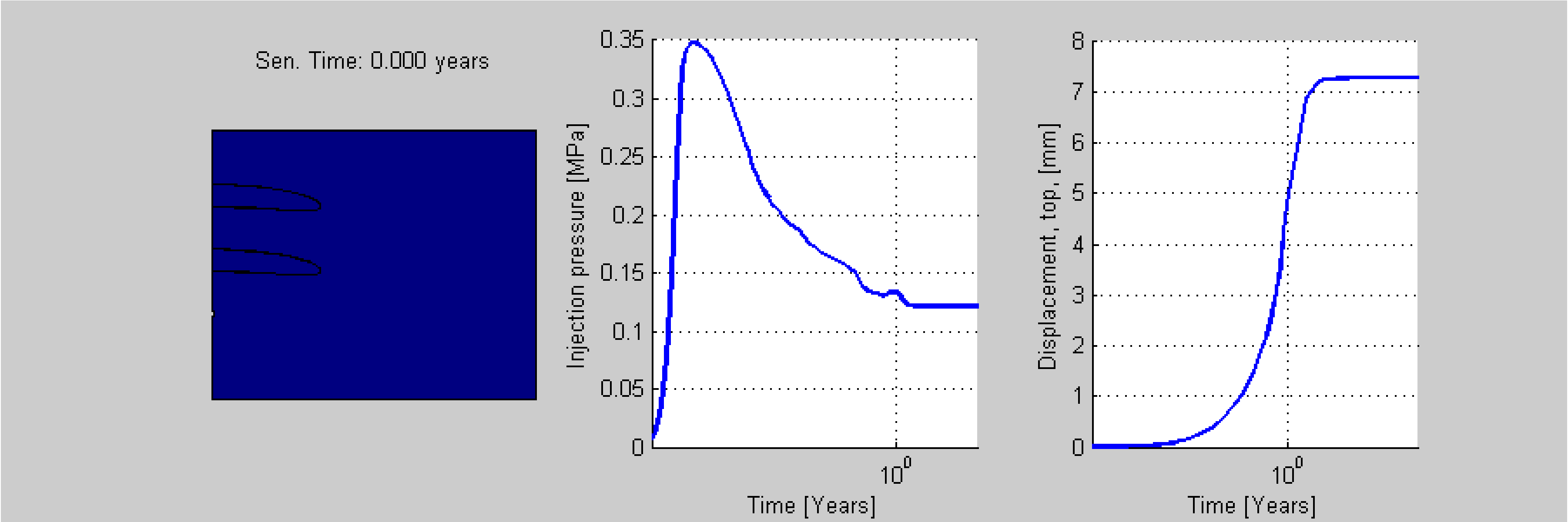
Example 3: Poroelasticity



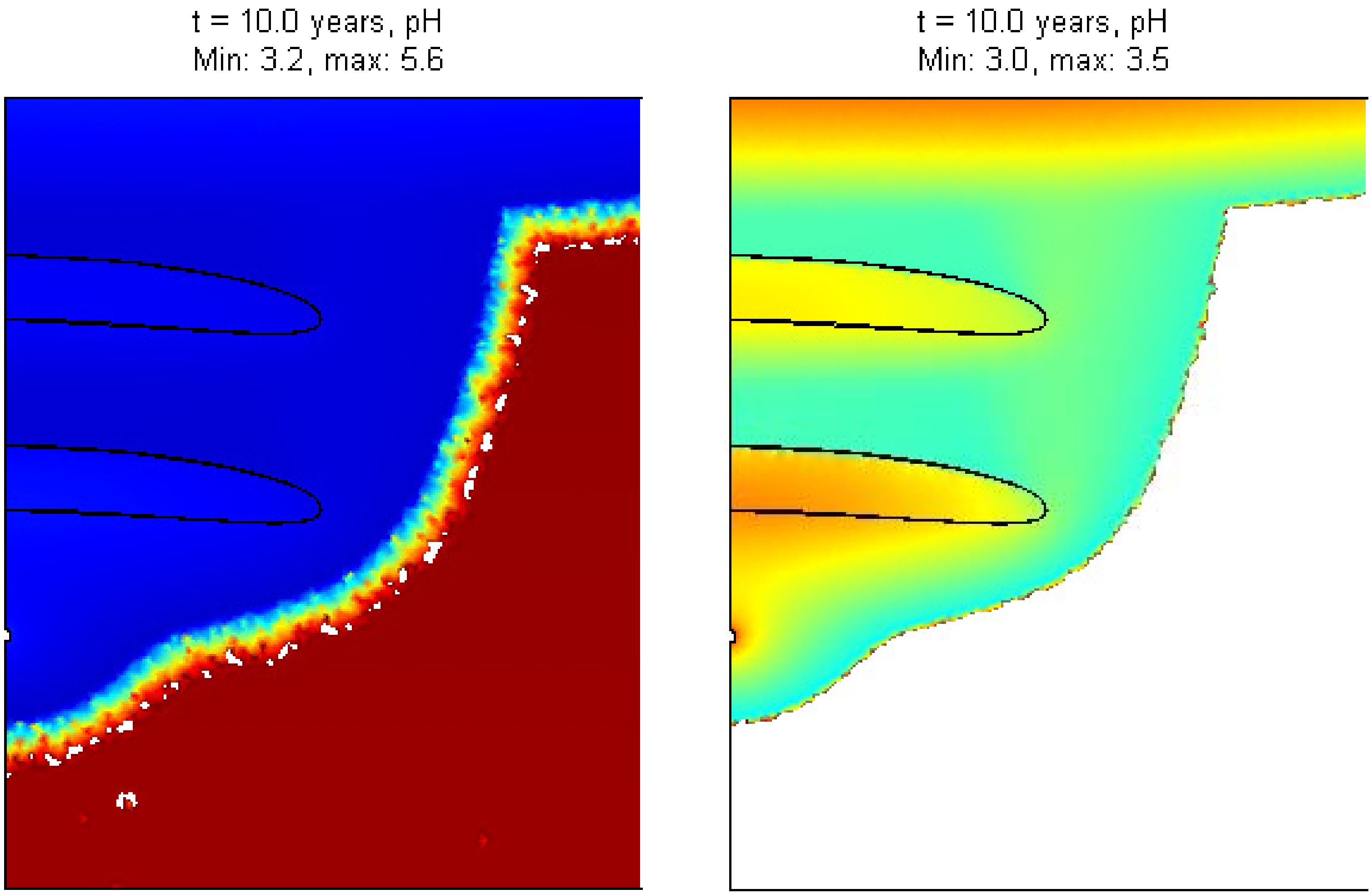




Wetting saturation Injection pressure Displacement



3: Poroelasticity



pH measurements are good detection methods
However, calcite buffers pH (maybe as much as 2)

4: Acidity (pH)

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Conclusion

- A robust model that considers many main features related to CO_2 injection has been developed
  - Improvements: More chemical reactions, more realistic geomechanical materials
- Most important short term storage mechanisms:
  - Residual and solubility trapping
- Remaining tasks:
  - Verification (compare with lab-experiment)
  - Simulation of “real-life” cases and risk assessment evaluation
- Thank you for your attention!