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Modeling of coupled hydro-mechanical processes occurring during CO_2 injection – example from In-Salah

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Agenda

- Introduction to two-phase flow modeling
  - Two-phase flow equations
    - Various formulations
    - Comparison, weaknesses, strengths, challenges
- Carbon Capture and Storage – CCS
  - Modelling of coupled hydro-mechanical processes occurring during CO_2 injection - example from In Salah

Two-phase flow equations

$$\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha)+\nabla\cdot(\rho_\alpha\mathbf{u}_\alpha)=\rho_\alpha q_\alpha$$ Mass balance

$$\mathbf{u}_\alpha=-\frac{k_{r\alpha}}{\mu_\alpha}\mathbf{K}(\nabla p_\alpha-\rho_\alpha\mathbf{g})$$ Darcy velocity

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

Two immiscible fluids in saturated porous media

Two-phase flow equations

$$\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha) + \nabla\cdot(\rho_\alpha \mathbf{u}_\alpha) = \rho_\alpha q_\alpha$$ Mass balance

$$\mathbf{u}_\alpha = -\frac{k_{r\alpha}}{\mu_\alpha}\mathbf{K}(\nabla p_\alpha - \rho_\alpha \mathbf{g})$$ Darcy velocity

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

But… there's also the global/total pressure!
Relating the partial pressures, here showing
Three definitions...

Various definitions of global/total pressure *ps*:

1. Flooding: $p_s = p_w + p_n$

2. Weighted: $p_s = S_w p_w + S_n p_n$

3. Fractional: $p_s = p_n - \int_S (f_w \frac{dp_c}{dS})(\xi) d\xi = p_w + \int_S (f_n \frac{dp_c}{dS})(\xi) d\xi$

   leading to relations between the derivatives;

   $\nabla p_s = \nabla p_w + f_n \cdot \nabla p_c = \nabla p_n - f_w \cdot \nabla p_c$

Some examples of two-phase flow eq.

- By manipulating the mass balances, one can obtain many different formulations. Two main groups:
- Pressure based:
  1. Partial pressure: pw – pn
  2. Flooding: ps – pc
- Saturation based:
  3. Pressure saturation: pw – Sn
  4. Pressure saturation: pn – Sw
  5. Fractional flow: ps – Sw
  6. Fractional flow: ps – Sn

Some examples of two-phase flow eq.

- By manipulating the mass balances, one can obtain many different formulations. Two main groups:
- Pressure based:
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  5. Fractional flow: ps – Sw
  6. Fractional flow: ps – Sn

Global/total pressure:

$6 \Rightarrow 12 \Rightarrow 18$

formulations

Assumptions and simplifications:

- Homogeneous and isotropic media
- Compressibility
- Gravity

Deriving the equations…

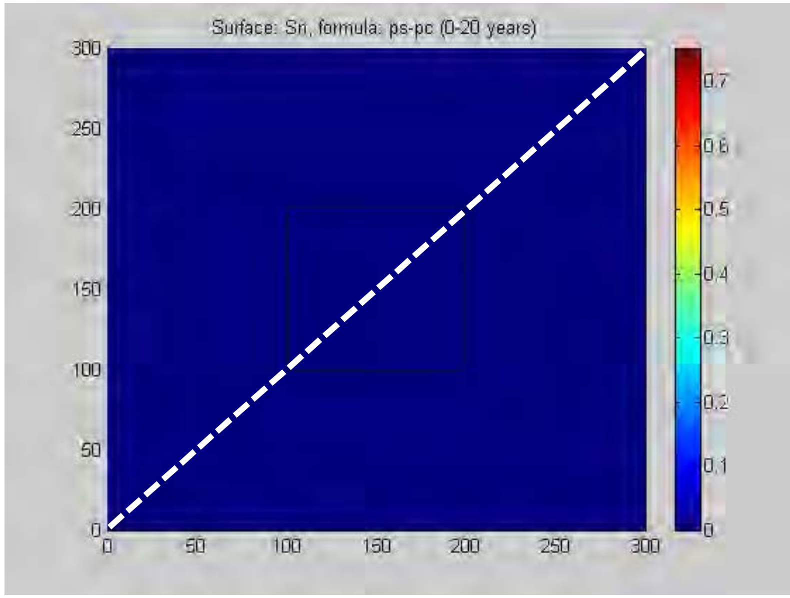
- Using any definition of ps:

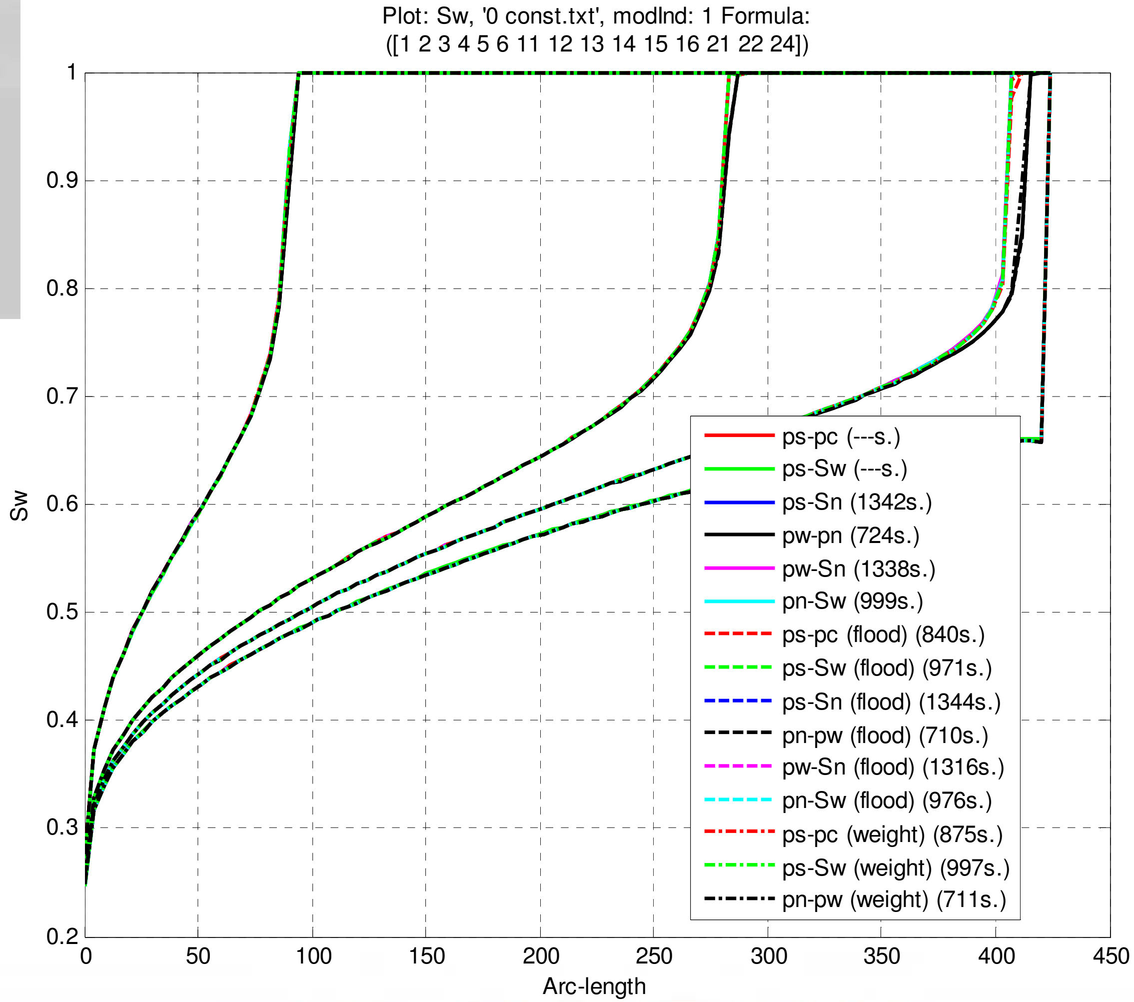
- p_w-equation:

$$-\phi \frac{\partial S_w}{\partial p_c} \frac{\partial p_w}{\partial t} - \nabla \cdot \frac{k_{rw}}{\mu_w} \mathbf{K} \nabla p_w = -\phi \frac{\partial S_w}{\partial p_c} \frac{\partial p_n}{\partial t}$$

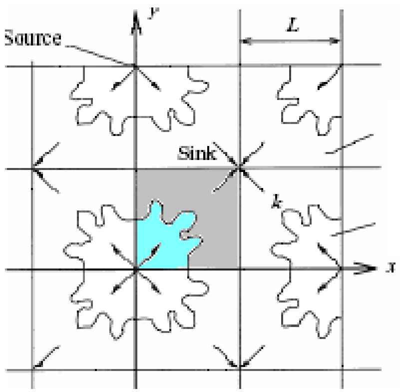
- p_n-equation:

$$-\phi \frac{\partial S_w}{\partial p_c} \frac{\partial p_n}{\partial t} - \nabla \cdot \frac{k_{rn}}{\mu_n} \mathbf{K} \nabla p_n = -\phi \frac{\partial S_w}{\partial p_c} \frac{\partial p_w}{\partial t}$$





Five spot model:



Simple and straight forward!

Assumptions and simplifications:

- Homogeneous and isotropic media
- Compressibility
- Gravity

Deriving the equations…

- Using the fractional definition:

$$\nabla p_s = \nabla p_w + f_n \cdot \nabla p_c = \nabla p_n - f_w \cdot \nabla p_c$$

- p_s-equation:

$$(\phi(S_n\rho_n c_{f,n} + S_w\rho_w c_{f,w}) + (\rho_n - \rho_n S_w + \rho_w S_w)\phi^0 c_R)\frac{\partial p_s}{\partial t} + \nabla\cdot((K_w f_n - K_n f_w)\frac{\partial p_c}{\partial S_w}\nabla S_w -$$

$$(K_n + K_w)\nabla p_s + (K_n\rho_n + K_w\rho_w)\mathbf{g}) = (\phi(\rho_w - \rho_n) + \phi(S_n\rho_n c_{f,n} f_w - S_w\rho_w c_{f,w} f_n)\frac{\partial p_c}{\partial S_w})\frac{\partial S_w}{\partial t}$$

- S_w-equation:

$$\phi\rho_w(1 - S_w c_{f,w} f_n \frac{\partial p_c}{\partial S_w})\frac{\partial S_w}{\partial t} - \nabla\cdot(K_w(\nabla p_s - f_n\frac{\partial p_c}{\partial S_w}\nabla S_w - \rho_w\mathbf{g})) = -S_w\rho_w(\phi c_{f,w} + \phi^0 c_R)\frac{\partial p_s}{\partial t}$$

Deriving the equations…

Assumptions and simplifications:

- Homogeneous and isotropic media
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- Using the fractional definition:

$$\nabla p_s = \nabla p_w + f_n \cdot \nabla p_c = \nabla p_n - f_w \cdot \nabla p_c$$

- p_s-equation:

$$(\phi(S_n\rho_n c_{f,n} + S_w\rho_w c_{f,w}) + (\rho_n - \rho_w)S_w + \rho_w S_w)\phi^0 c_R)\frac{\partial p_s}{\partial t} + \nabla\cdot((K_w f_n - K_n f_w)\frac{\partial p_c}{\partial S_w}\nabla S_w -$$

$$(K_n + K_w)\nabla p_s + (K_n\rho_n + K_w\rho_w)\mathbf{g}) = (\phi(\rho_w - \rho_n) + \phi(S_n\rho_n c_{f,n} f_w - S_w\rho_w c_{f,w} f_n)\frac{\partial p_c}{\partial S_w})\frac{\partial S_w}{\partial t}$$

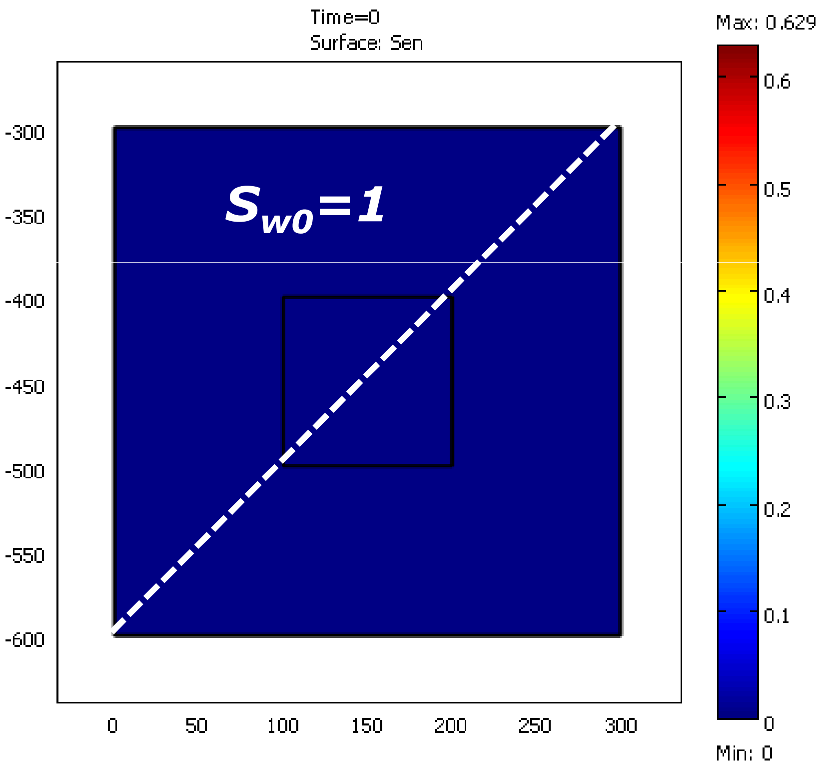
- S_w-equation:

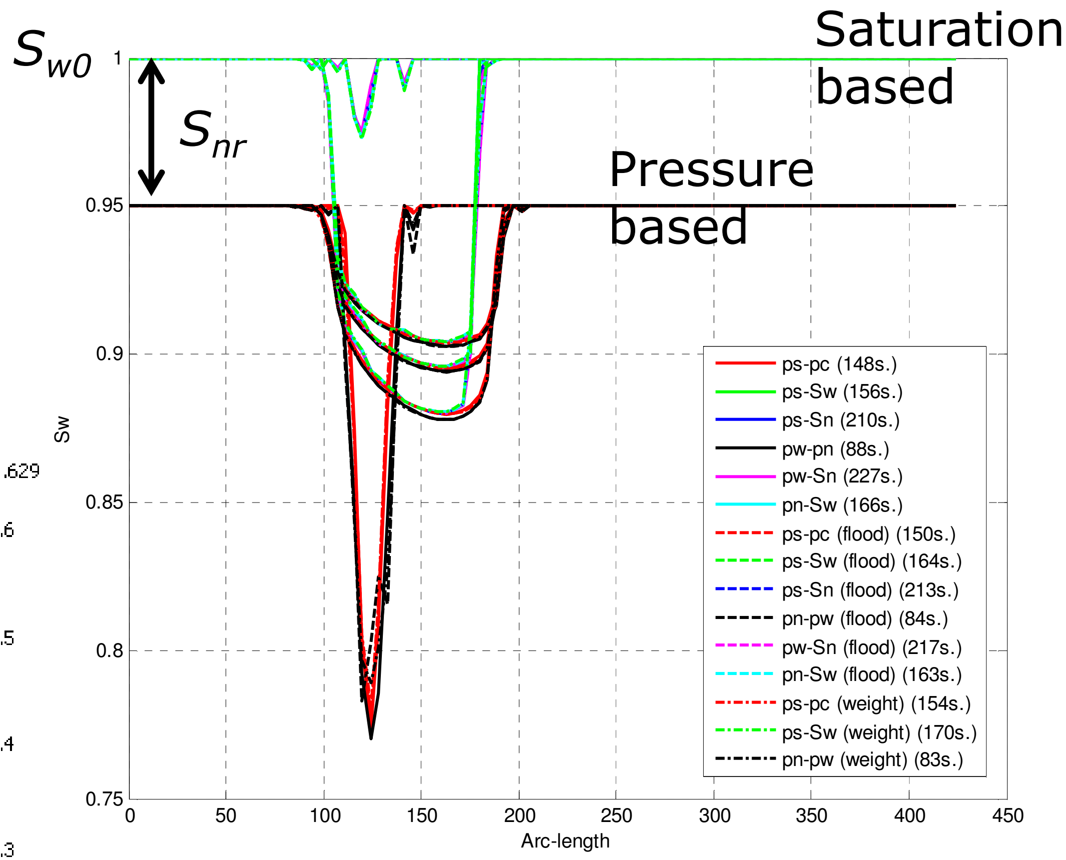
$$\phi\rho_w(1 - S_w c_{f,w} f_n \frac{\partial p_c}{\partial S_w})\frac{\partial S_w}{\partial t} - \nabla\cdot(K_w(\nabla p_s - f_n\frac{\partial p_c}{\partial S_w}\nabla S_w - \rho_w\mathbf{g})) = -S_w\rho_w(\phi c_{f,w} + \phi^0 c_R)\frac{\partial p_s}{\partial t}$$

Beware of artificial "source-terms" in pressure based forms!!

Saturation based:
Gives S_w/S_n directly:

$$S_{wr} \leq S_w \leq S_{w0}$$





Pressure based gives S_w/S_n through capillary pressure functions:

$$S_{ew} = S_{ew}(p_c)$$

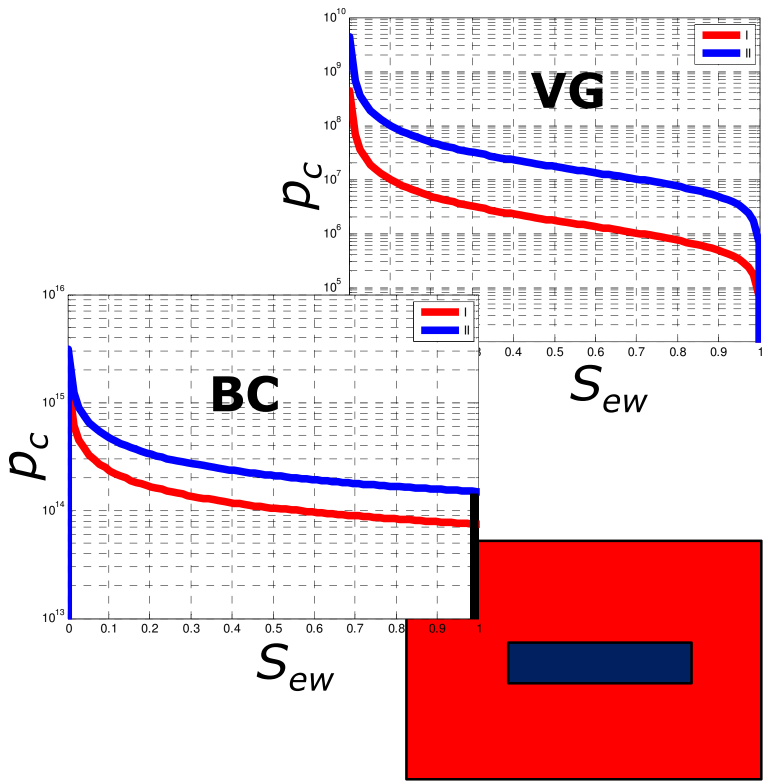
$$S_w = S_{ew}(1 - S_{wr} - S_{nr}) + S_{wr}$$

$$S_{wr} \leq S_w \leq 1 - S_{nr} (\leq S_{w0})$$

Example of residual trapping

Heterogeneous reservoir…

- A whole different story; when two neighboring domains have different capillary functions:



1. <u>Continuity in flux</u>: the flux of both phases have to be continuous across the interface
2. **<u>Continuity in capillary pressure</u>**, and the phase pressure that is mobile on both sides of the interface
3. **<u>Discontinuous phase saturations</u>**

Heterogeneous reservoir…

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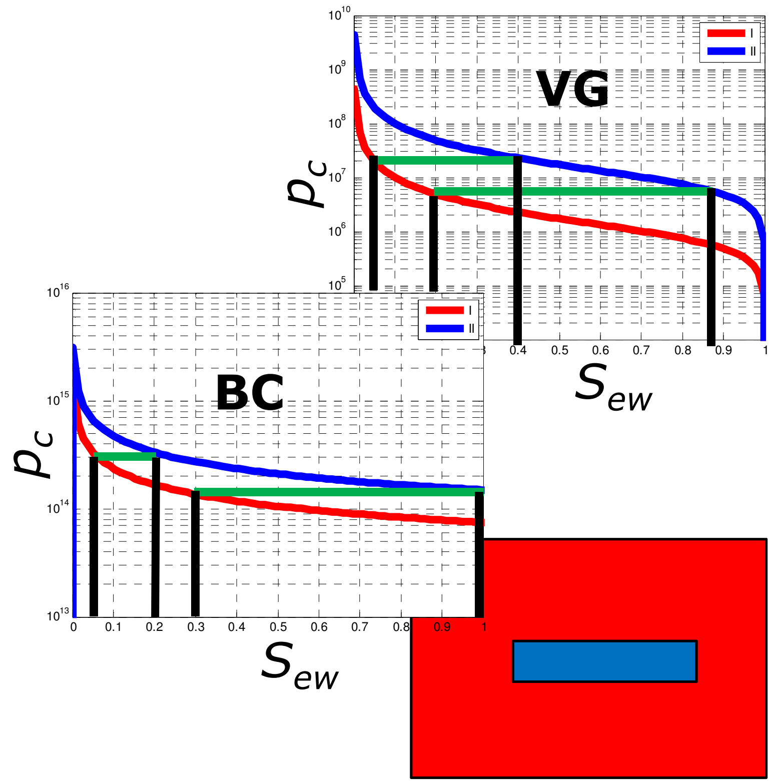

1. Continuity in flux: the flux of both phases have to be continuous across the interface
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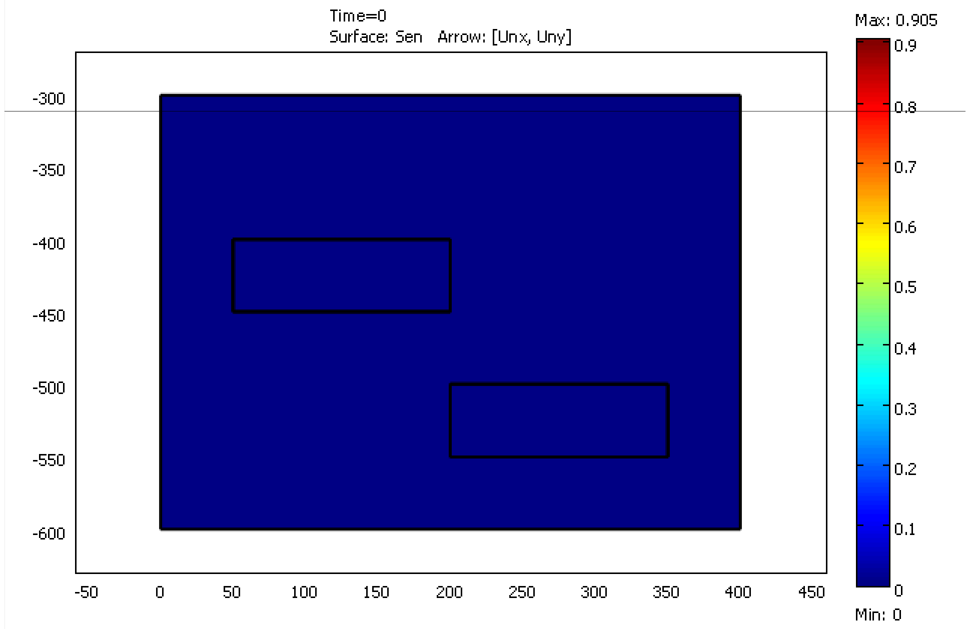
3. **Discontinuous phase saturations**

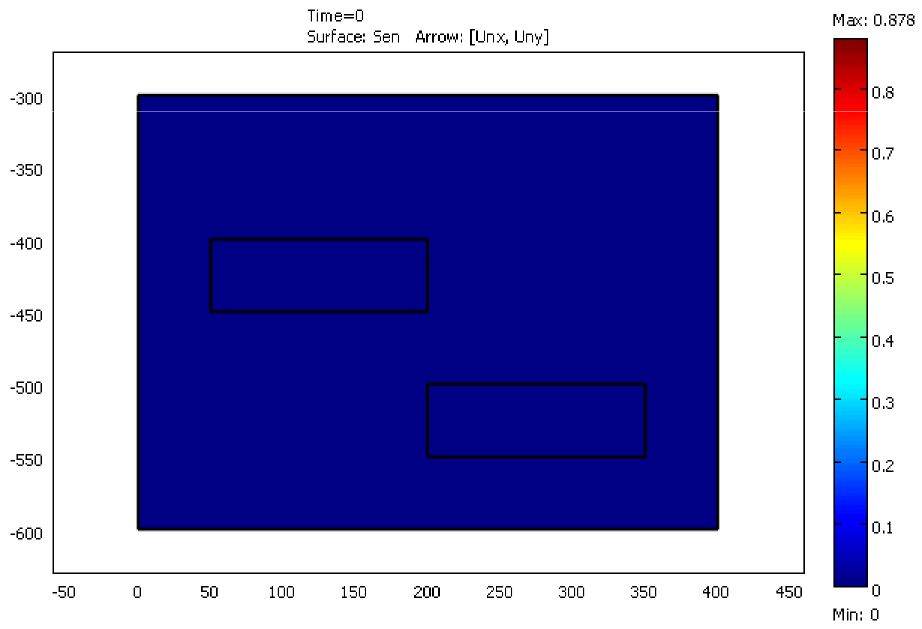
Discontinuity:

Entry pressure VS permeability

Discontinuity due to entry pressure



Discontinuity due to Permeability



Summary

- Easy to derive a set of equations for two-phase flow
- Heterogeneous media can be “easily” handled:
  - Constraining the saturations on opposite sides of an interface to a capillary function ratio
- p_n-S_w and p_w-S_n are robust candidates for two-phase flow modeling
  - Handles discontinuities, also faults and fractures, and residual saturations, but lack speed
- Pressure based are the fastest
  - But, least robust as it’s lacking some important features; support for residual saturations and heterogeneities

Carbon Capture and Storage - CCS

Example from In-Salah, Algeria

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Introduction

- At In Salah, Algeria, excess CO_2 from the produced oil and gas is re-injected (app. 1 mill. tons/year) into the ground as part of a CO_2 storage demonstration project
- A significant heave at the injection sites was observed (InSAR): 5-8 mm/yr (as much as 15 mm after 3 years)
  - Several kilometers footprint. Modeling has verified the observations
- Still, we wanted to apply our model to a “realistic” case:
  - For “verification” and see if there is any lessons to be learned

Biot linear poroelasticity equation - short

- Linear Biot poroelasticity:
  - Elastic response of fluid saturated porous media; linear elastic solids undergoing quasistatic small deformations:

$$\nabla \cdot [\boldsymbol{\sigma}] = -\mathbf{F}(\rho_{f0})$$

$$\boldsymbol{\sigma} = \mathbf{D}_d \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0$$

Biot linear poroelasticity equation - short

- Linear Biot poroelasticity:
  - Elastic response of fluid saturated porous solid; linear elastic solids undergoing quasistatic small deformations

$$\nabla \cdot [\boldsymbol{\sigma}] = -\mathbf{F}(\rho_f)$$

$$\boldsymbol{\sigma} = \mathbf{D}_d \boldsymbol{\varepsilon} + \boldsymbol{\sigma}_0 - \alpha_{biot} p \mathbf{I}$$

Coupling

$$Q = -\alpha_{biot} \frac{\partial \varepsilon_v}{\partial t}$$

$$\phi = (1 - \varepsilon_v)\phi^0$$

$$\phi \rho_w (1 - S_w c_{f,w} f_n \frac{\partial p_c}{\partial S_w}) \frac{\partial S_w}{\partial t} - \nabla \cdot (K_w (\nabla p_s - f_n \frac{\partial p_c}{\partial S_w} \nabla S_w - \rho_w \mathbf{g})) = q_w \rho_w - S_w \rho_w (\phi c_{f,w} + \phi^0 c_R) \frac{\partial p_s}{\partial t}$$

Studies to learn some lessons

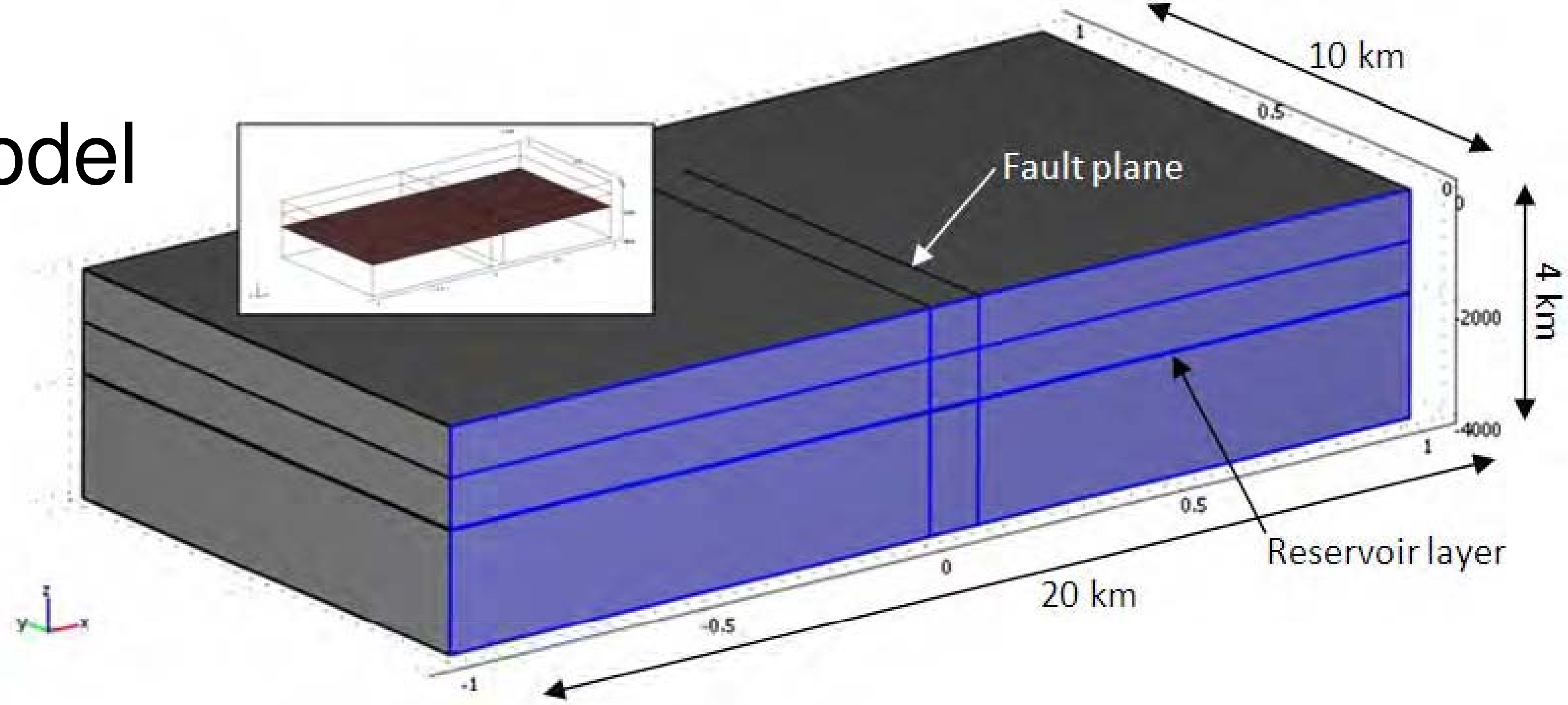
1. Base case
   - Simplified, best guess model
2. Fracture case
   - High-permeable lower-caprock
3. Fault case
   - Best guess model with a vertical fracture/fault plane intersecting the caprock

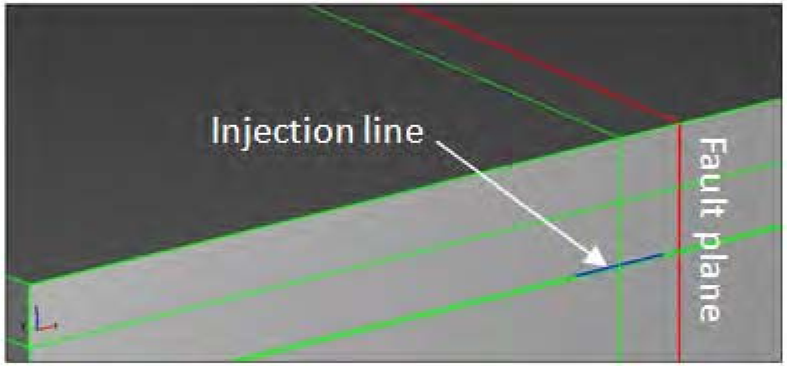
Layer	Depth, [m] (thickness, [m])	Hydraulic properties	Elastic properties
Cretaceous sandstone and mudstone overburden	0-900 (900)	$K = 10^{-19}$ m^2 $\phi = 0.17$ p_d = 1 MPa	E = 7 GPa ν = 0.15
Carboniferous mudstone	900-1800 (900)	$K = 10^{-19}$ m^2 $\phi = 0.17$ p_d = 1 MPa	E = 7 GPa ν = 0.15
(High permeable, lower caprock)	1640-1800 (160)	(K = 200 mD, $\phi = 0.17$, p_d = 1 MPa)	(E = 6 GPa ν = 0.2)
C10.2 Sandstone	1800-1820 (**20**)	K_{eff} = 200 mD ϕ = 0.15-0.2 (≈0.17) p_d = 1 MPa	E = 6 GPa ν = 0.2
D70 mudstone underburden	1820-4000 (2180)	$K = 10^{-19}$ m^2 $\phi = 0.17$ p_d = 1 MPa	E < 5 GPa ν = 0.15

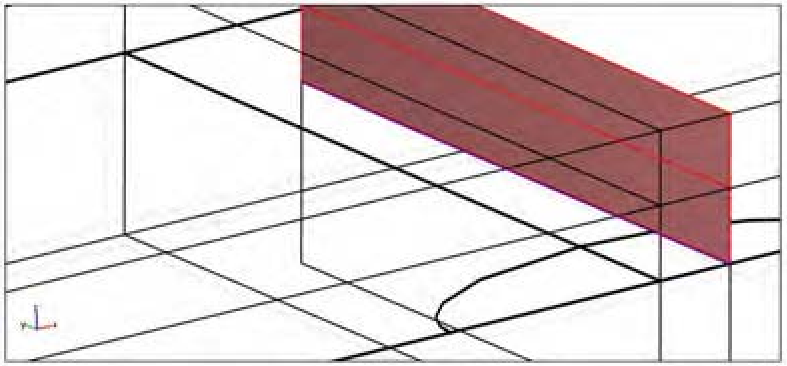
Fault line

Injection line

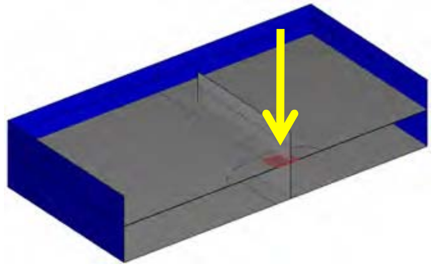
Model


10 km
Fault plane
4 km
Reservoir layer
20 km
-2000
-4000
0
0.5
1
-0.5
-1

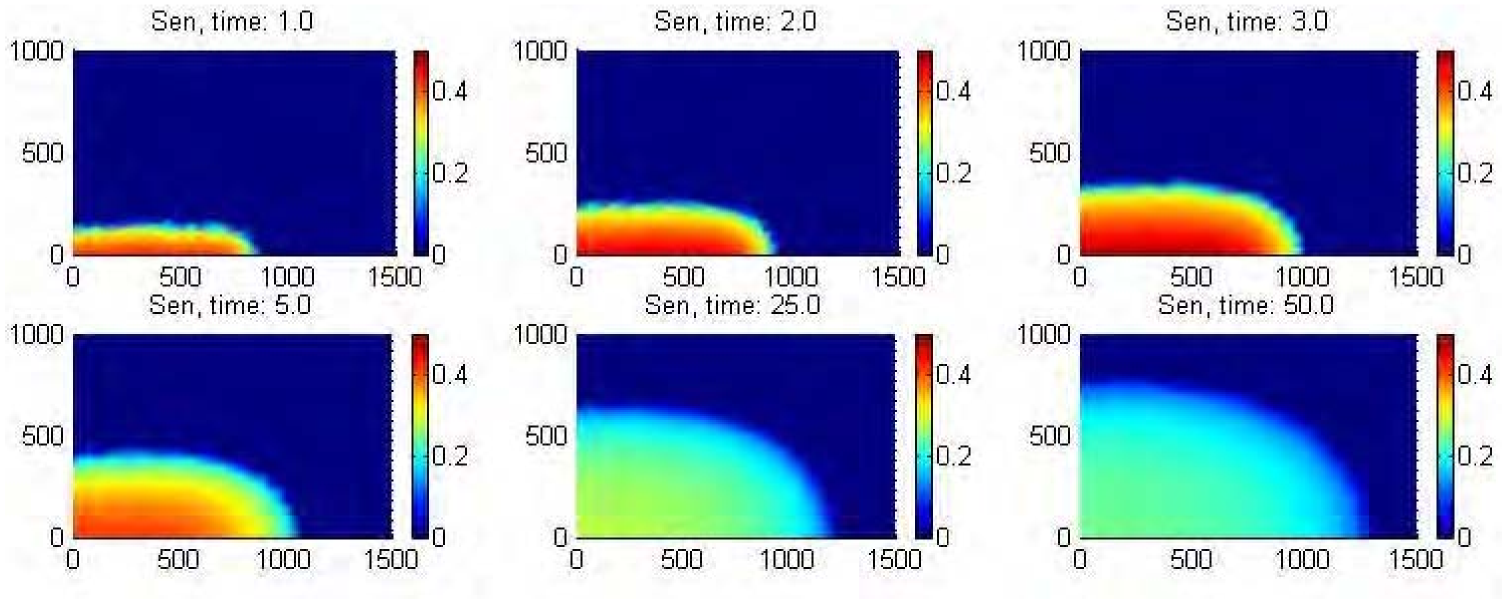

Injection line
Fault plane



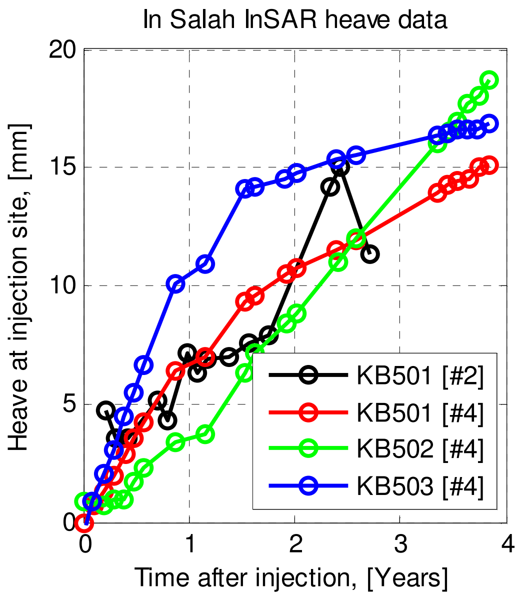
Results (base case)

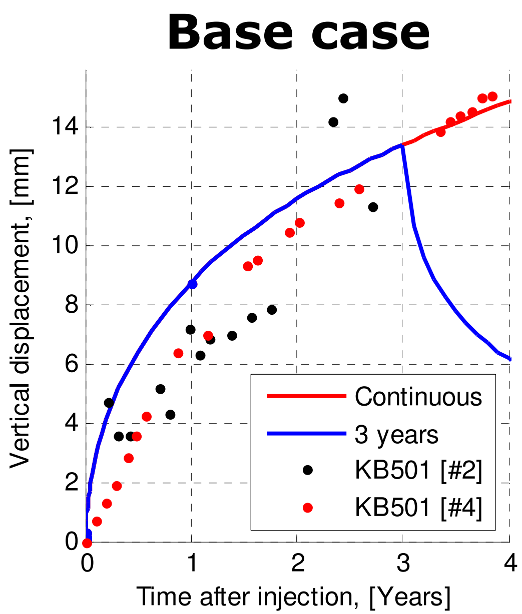


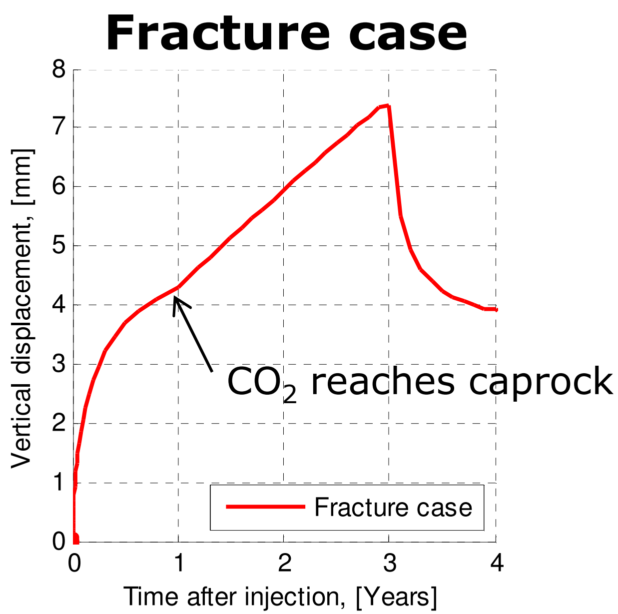
- The base case model is solved for injection of CO_2 over 3 years and 50 years



Snapshots of the CO_2 plume at various times (seen from above, along the top surface of the reservoir; -1800 m).

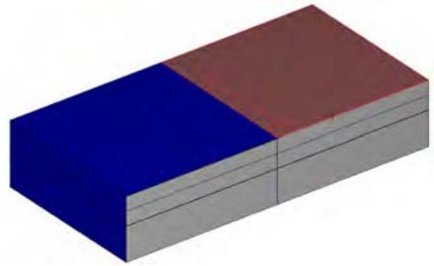




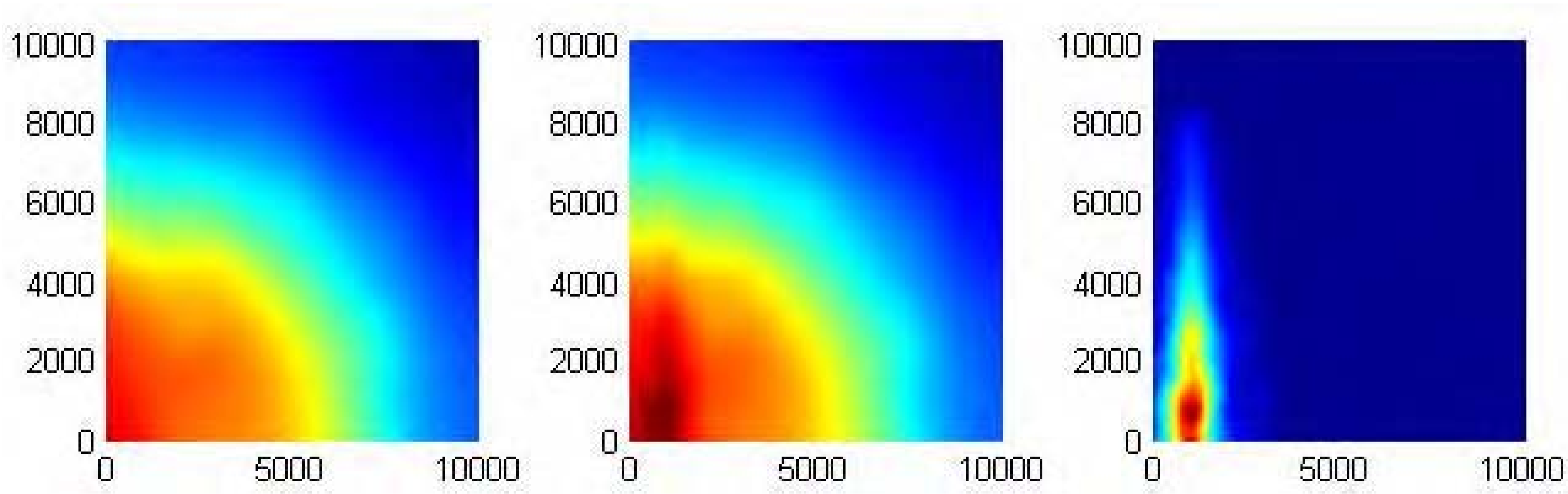


- Comparing modeled vs. measured:
  - Good agreement (except fractured case)
- Comparing cases:
  - Heave is not comparable, however, the shape is interesting and may say something about the hydraulic properties

Results, fault case



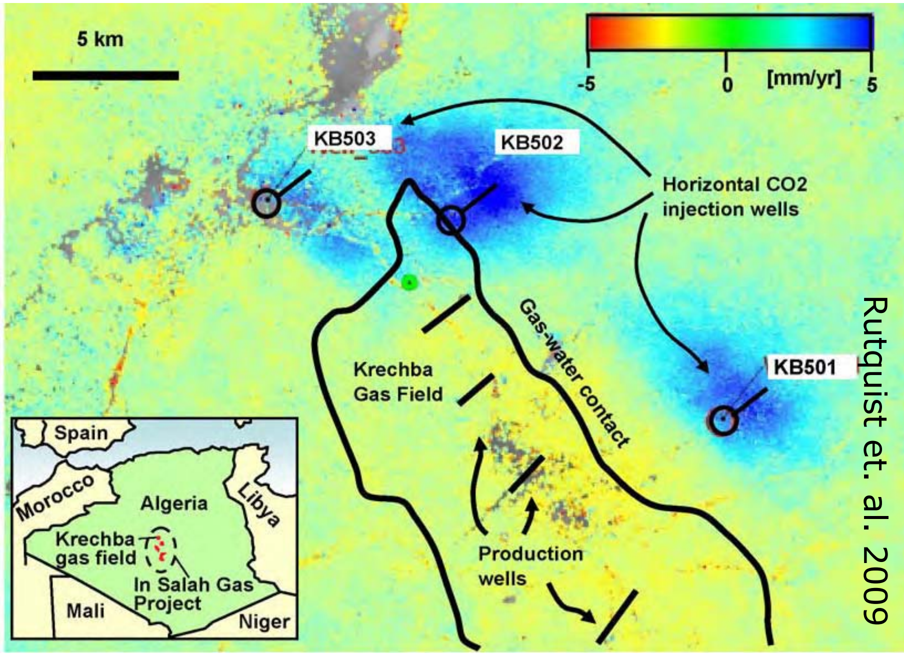
- Snap shots vertical displacement after 3 years. Color scale is 0-15 mm, in difference plot: 0-3 mm



The heave is **not** due to leakage through the fault.

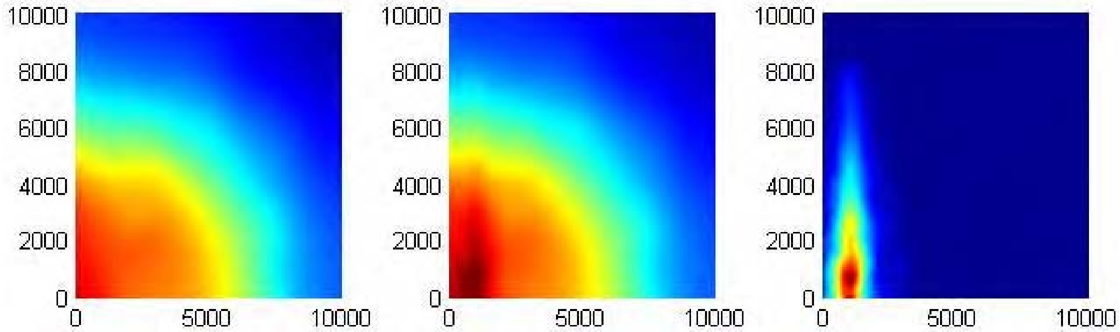
- Fault case:

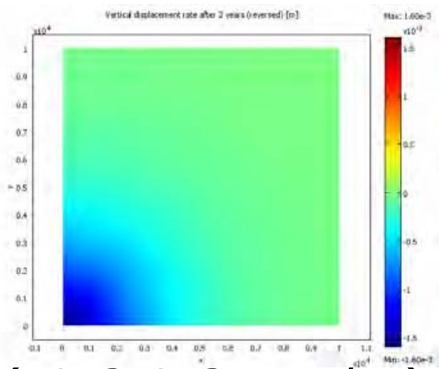
  A large fault can give a distinct heave pattern at the surface, even out of reach from the plume



Rutquist et. al. 2009

Total vertical displacement after 3 years. (0-15mm and 0-3 mm)





Rate of vertical displacement after 3 years (-1.6-1.6 mm/yr)

Summary

- Even a simple model is able to capture the main effects of a real case
- The shape of the heave curve at the top surface can say something about the geology and hydraulic properties
  - Here a fractured zone above the injection layer
- Fault/fracture planes give visible footprints on the surface and whether it behaves as a seal or a conduit for flow