COMSOL
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# Geologic CO2 storage: Implications of Two-Phase Flow on Injection-Induced stress on Faults

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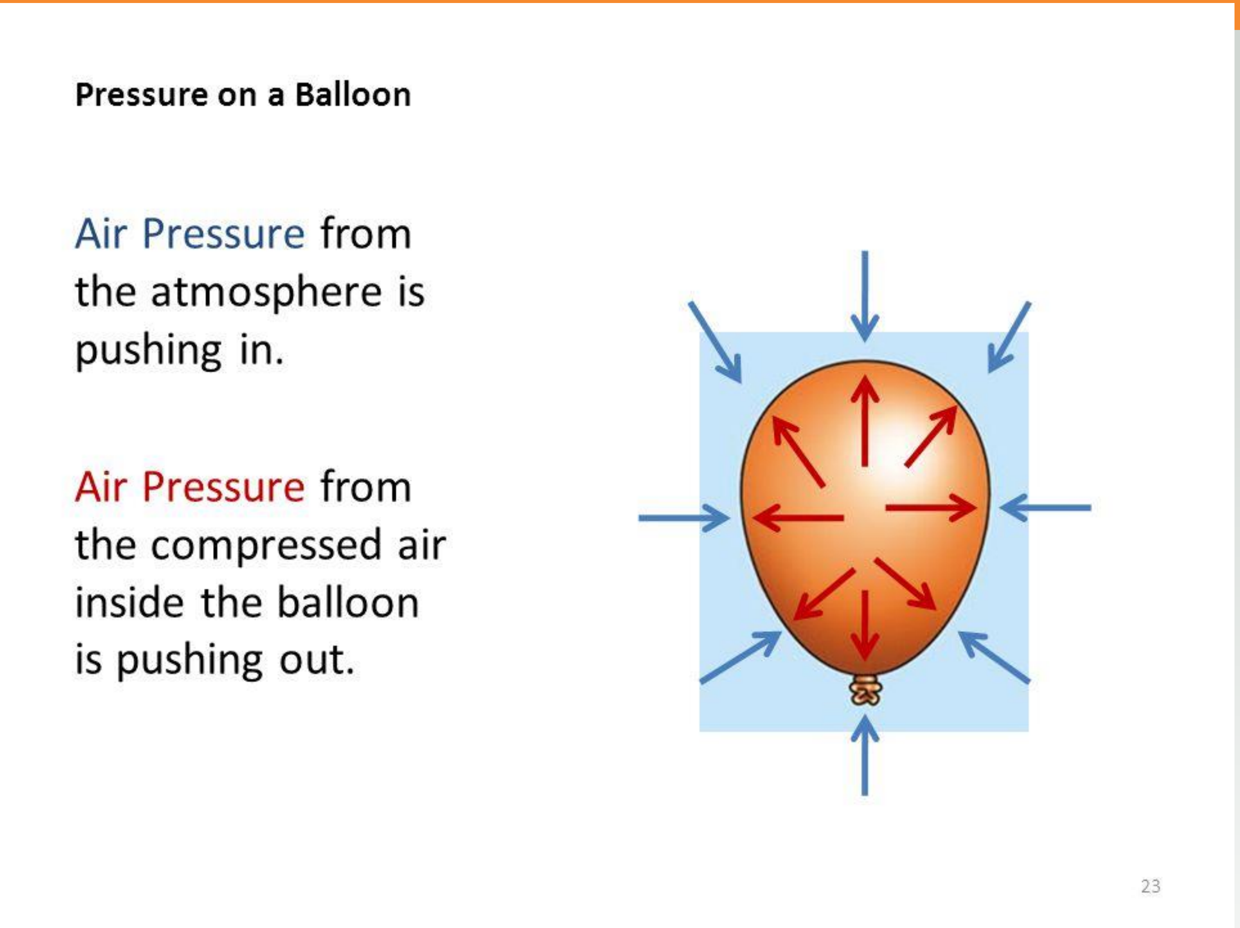
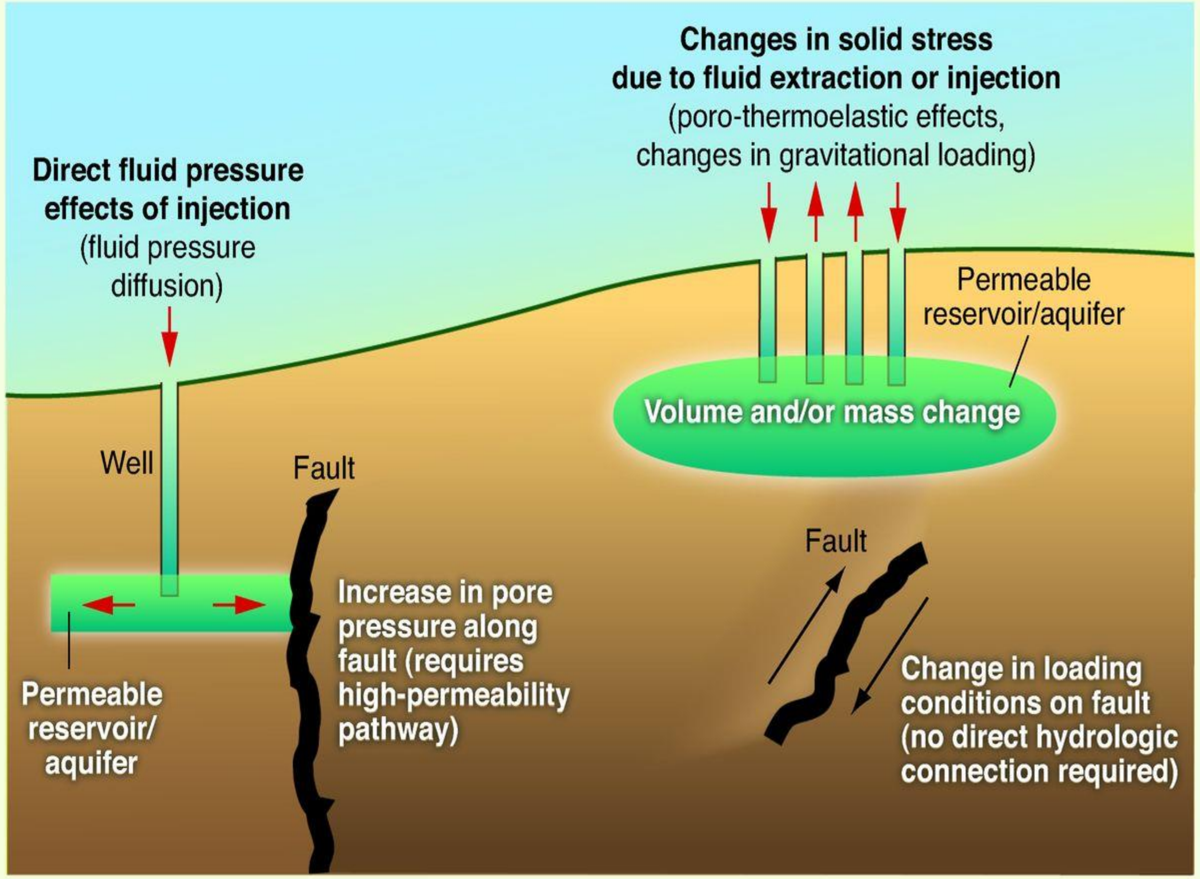
# Real Examples of Fluid-Solid Interactions



**Pressure on a Balloon**

Air Pressure from the atmosphere is pushing in.

Air Pressure from the compressed air inside the balloon is pushing out.



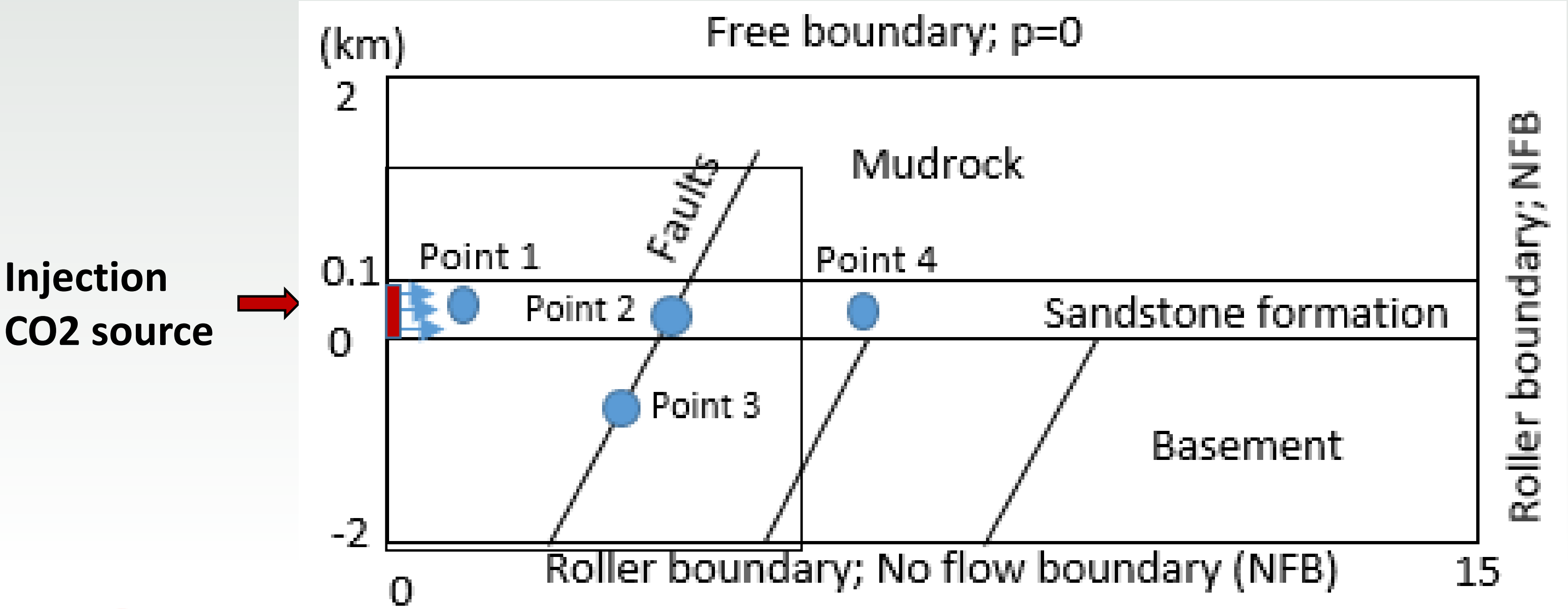
# Motivation

- Use of single phase fluid flow model coupled with the geomechanics may be inaccurate
- Traditional multi-phase poro-mechanical model suffer from drawbacks resolved by COMSOL

| Traditional models | COMSOL Multiphysics |
|---|---|
| Use of finite difference | Finite element |
| Partially implicit-partially explicit method (IMPES) | Fully implicit |
| Employs linear solver which cannot solve discretized non-linear equations | Employs fast non-linear solvers-Newton Rhapson iteration scheme |
| Meshes are cartesian, difficult to program non-uniform geometries like faults | Automatic meshing system-capable of automatically refining complex domains |

# Objectives

- Evaluate the effect of two phase flow simulation on the stress on hydraulically connected conductive faults during CO2 sequestration
- Compare the geomechanical effects of two phase flow with single phase flow conditions



# Single phase Poro-Mechanical Equations using COMSOL Multiphysics

- Fluid to solid coupling equation using **Solid mechanics interface**

$$\sigma = C\varepsilon - \alpha p_f I \qquad (1)$$

- Mass conservation equation defined via **PDE user interface**,

$$\rho_w S_{\in w}\frac{\partial(p_w)}{\partial t} + \nabla.\rho_w[-\lambda_w(\nabla p_w + \rho_w g \nabla h)] = -\alpha\frac{\partial(\rho_w \varepsilon_{vol})}{\partial t} \qquad (2)$$

- Solid deformation complies with force equilibrium:

$$\nabla.\sigma + (\rho_w \varphi + \rho_d)\underset{g}{\rightarrow} = \underset{0}{\rightarrow} \qquad (3)$$

Where,

$$S_{\in w} = \varphi c_w + (\alpha - \varphi)\frac{1-\alpha}{K_d}$$

$$K_d = \frac{2\nu(1+G)}{3}/(1-2\nu),\ \lambda_w = \frac{k}{\mu_w}$$

$C$ **= elasticity matrix**
$\alpha$ **= biot's constant**
**I = identity matrix**

$\rho_w$ **= density of water**
$p_w$ **= pore pressure**
$\lambda_w$ **= mobility of water,** $m^2$**/Pa.s**

$S_{\in w}$**= constrained water fluid storage coefficient**

$\varepsilon_{vol}$ **= volumetric strain**
$k$ **= absolute permeability**
**G = shear modulus**
$c_w$ **= compressibility of water**

$\varphi$ **= porosity**
$\mu_w$ **= viscosity of water**
$\nu$ **= poisson's ratio**
$K_d$ **= drained bulk modulus**

# Two-Phase Poro-Mechanical Model using COMSOL Multiphysics

- Constitutive equation of **Solid mechanics interface**

$$\sigma = C\varepsilon - \alpha p_f I \qquad (1)$$

Solid-to-fluid coupling

- Two phase immiscible flow equations defined via **PDE user interface**,

$$\rho_g S_g S_{\in g}\frac{\partial(p_w)}{\partial t} + \left(\varphi\rho_g + \rho_g S_g S_{\in g}\frac{\partial p_c}{\partial S_g} + \alpha\rho_g\varepsilon_{vol}\right)\frac{\partial(S_g)}{\partial t} + \nabla.\rho_g\left[-\lambda_g\left(\nabla p_w + \frac{\partial p_c}{\partial S_g}\nabla S_g + \rho_g g\nabla h\right)\right] = \boxed{-\alpha S_g\frac{\partial(\rho_g\varepsilon_{vol})}{\partial t}} \qquad (2)$$

$$\rho_w(1 - S_g)S_{\in w}\frac{\partial(p_w)}{\partial t} - (\varphi\rho_w + \alpha\rho_w\varepsilon_{vol})\frac{\partial(S_g)}{\partial t} + \nabla.\rho_w[-\lambda_w(\nabla p_w + \rho_w g\nabla h)] = \boxed{-\alpha(1 - S_g)\frac{\partial(\rho_w\varepsilon_{vol})}{\partial t}} \qquad (3)$$

- Solid deformation complies with force equilibrium:

$$\nabla.\sigma + \left(\left((1 - S_g)\rho_w + S_g\rho_g\right)\varphi + \rho_d\right)\overrightarrow{g} = \overrightarrow{0} \qquad (4)$$

Where,

$$S_{\in g} = \varphi c_g + (\alpha - \varphi)\frac{1-\alpha}{K_d}$$

$$S_{\in w} = \varphi c_w + (\alpha - \varphi)\frac{1-\alpha}{K_d}$$

$$K_d = \frac{2\nu(1+G)}{3}/(1 - 2\nu),\ \lambda_g = \frac{k_g}{\mu_g},\ \lambda_w = \frac{k_w}{\mu_w}$$

**$C$ = elasticity matrix**
**$\alpha$ = biot's constant**
**$p_f$ = pore pressure**
**I = identity matrix**
**$S_g$ = gas saturation**
**$p_w$ = water phase pressure**
**$\varepsilon_{vol}$ = volumetric strain**
**$\varphi$ = porosity**
**$\mu_g$ = viscosity of gas**
**$\mu_w$ = viscosity of water**
**$c_g$ = compressibility of gas**

**$\rho_g$= density of CO2**
**$\rho_w$ = density of water**
**$\lambda_g$ = mobility of gas, $m^2$/Pa.s**
**$\lambda_w$ = mobility of water, $m^2$/Pa.s**
**$S_{\in g}$= constrained gas phase storage coefficient**
**$S_{\in w}$= constrained water phase storage coefficient**
**$p_c$ = capillary pressure**
**$k_w$ = effective permeability of water**
**$k_g$ = effective permeability of gas**
**$c_w$ = compressibility of water**

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# Model Properties and Boundary Conditions

- The top, bottom and side boundaries except the fluid inlet are no flow boundaries.
- A roller is imposed on the bottom and side boundaries. The top surface is free.
- The initial conditions for the change in pore pressure, $p_f$ and stresses are,

$$p_f(x, t = 0) = 0\,;$$
$$\sigma_{xx}(t = 0) = \sigma_{zz}(t = 0) = \sigma_{yy}(t = 0) = 0$$

**Chang and Segall 2016**

| Model properties | Unit | Mudrock | Sandstone | Basement | Fault |
|---|---|---|---|---|---|
| Permeability | $\mathrm{m}^2$ | $10^{-19}$ | $6.4 \times 10^{-14}$ | $2 \times 10^{-17}$ | $10^{-13}$ |
| density | $\mathrm{kg/m^3}$ | 2600 | 2500 | 2740 | 2500 |
| Shear modulus | GPa | 11.5 | 7.6 | 25 | 6 |
| Biot’s constant | - | 0.35 | 0.55 | 0.24 | 0.79 |
| Poisson's ratio | - | 0.3 | 0.15 | 0.2 | 0.2 |
| Porosity | - | 0.1 | 0.25 | 0.05 | 0.02 |
| Friction factor, f | - | 0.5 | 0.6 | 0.6 | 0.75 |

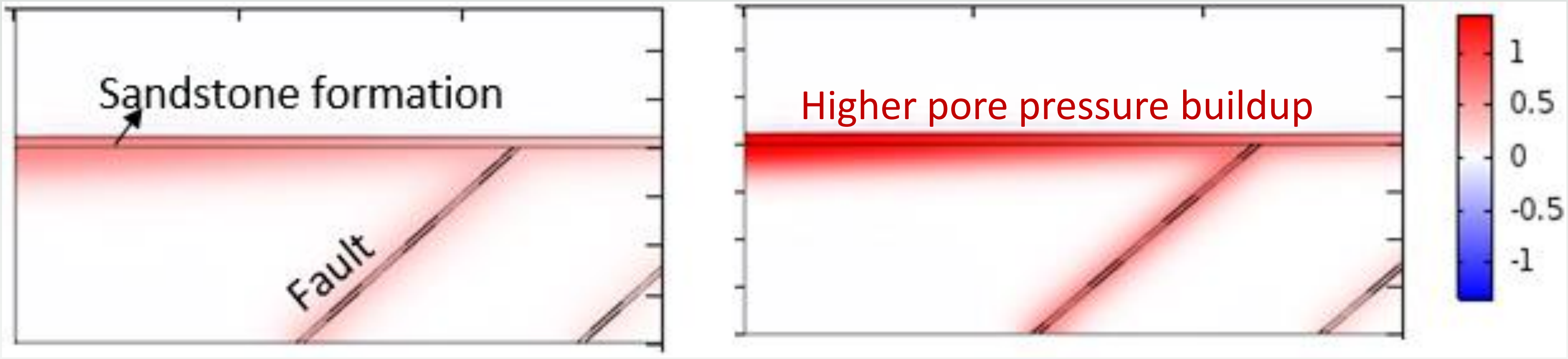
| Parameters | Unit | Value |
|---|---|---|
| Volumetric rate (Q) | $\mathrm{m^3/day}$ | 3000 |
| Length of target formation (L) | m | 15000 |
| Duration of injection | days | 30 |
| Thickness of target formation | m | 100 |
| Initial formation pressure (Pi) | MPa | 20 |
| Initial formation temperature (T) | F | 150 |
| Depth of target formation | m | 1900 |

# Numerical Results and Analysis- Change in pore pressure, $\Delta p_f$

**Single Phase flow**
**(Injecting water in aquifer)**

**Two Phase Flow**
**(Injecting CO2 in aquifer)**

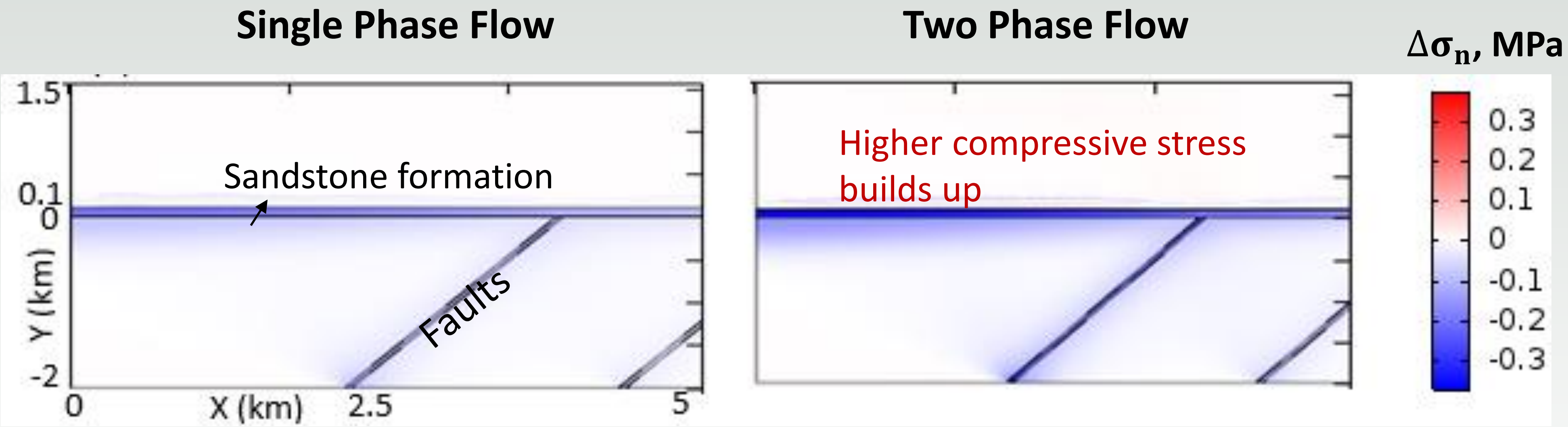
**At 150 days**
**(post injection)**



- **Slower pressure diffusion due to lower hydraulic diffusivity of two phase flow causes higher pore pressure build up**

# Change in Normal stress, $\Delta\sigma_n$ on plane parallel to faults

**At 150 days (post injection)**



Sandstone formation

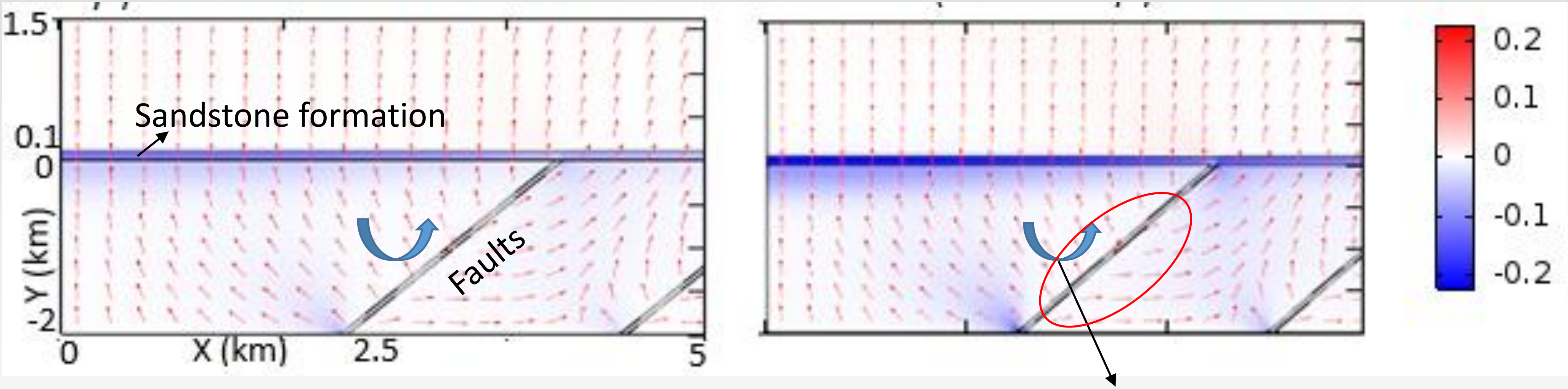
Faults

Higher compressive stress builds up

- **Higher Compressive stress changes occurs in faults under two-phase flow conditions**

# Change in Shear stress, $\Delta\tau_s$ along with displacement, u on faults

**At 150 days (post injection)**



**Single Phase Flow**

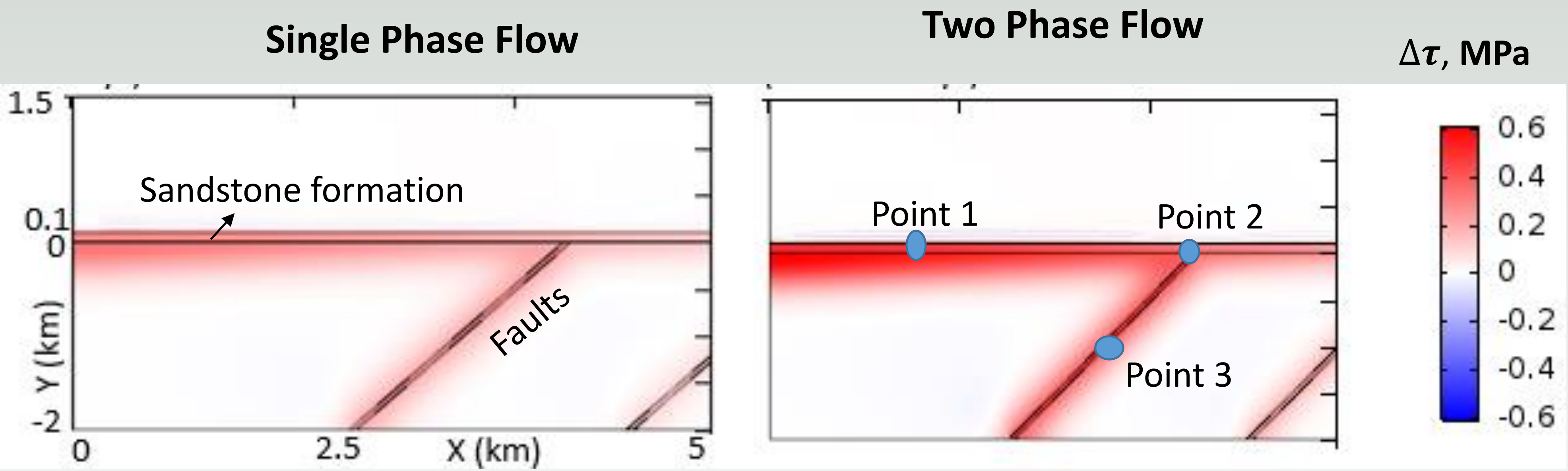
**Two Phase Flow**

**$\Delta\tau_s$, MPa**

Displacement vector changes from lateral
to vertical causing slight positive shear stress change

# Change in Coulomb stress, $\Delta\tau = \Delta\tau_s + f(\Delta\sigma_n + \Delta p_f)$

**At 150 days (post injection)**

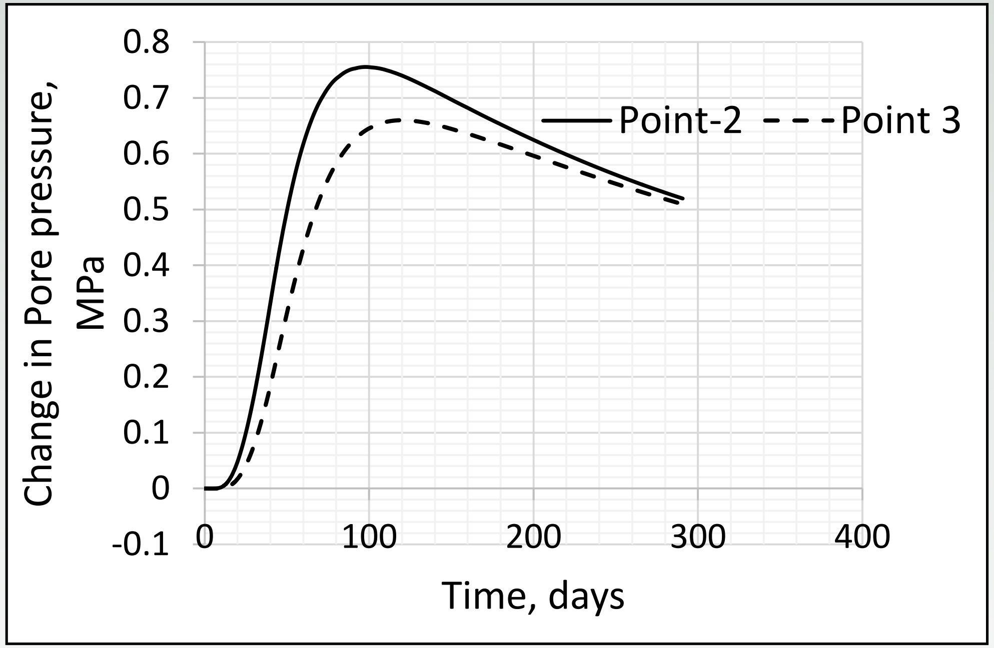


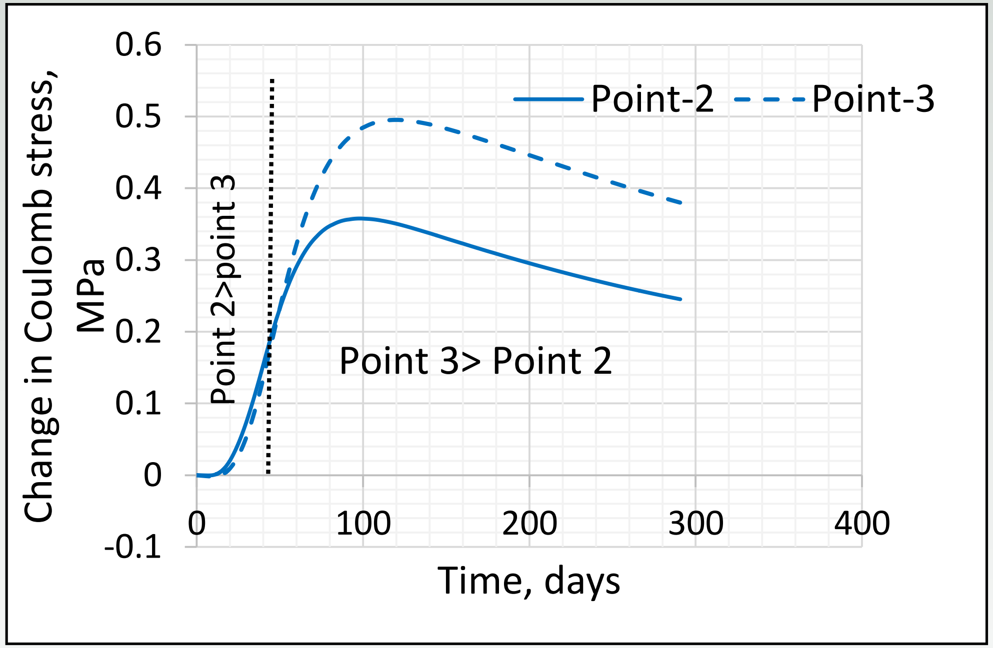
- **Coulomb stress change resemble pore pressure change**
- **Coulomb stress change is higher under two phase flow condition**

# Pore pressure and Coulomb stress changes at Points 2, and 3 in faults

$$Coulomb\ stress, \Delta\tau = \Delta\tau_s + f(\Delta\sigma_n + \Delta p_f)$$

## *Two Phase Flow Simulation*

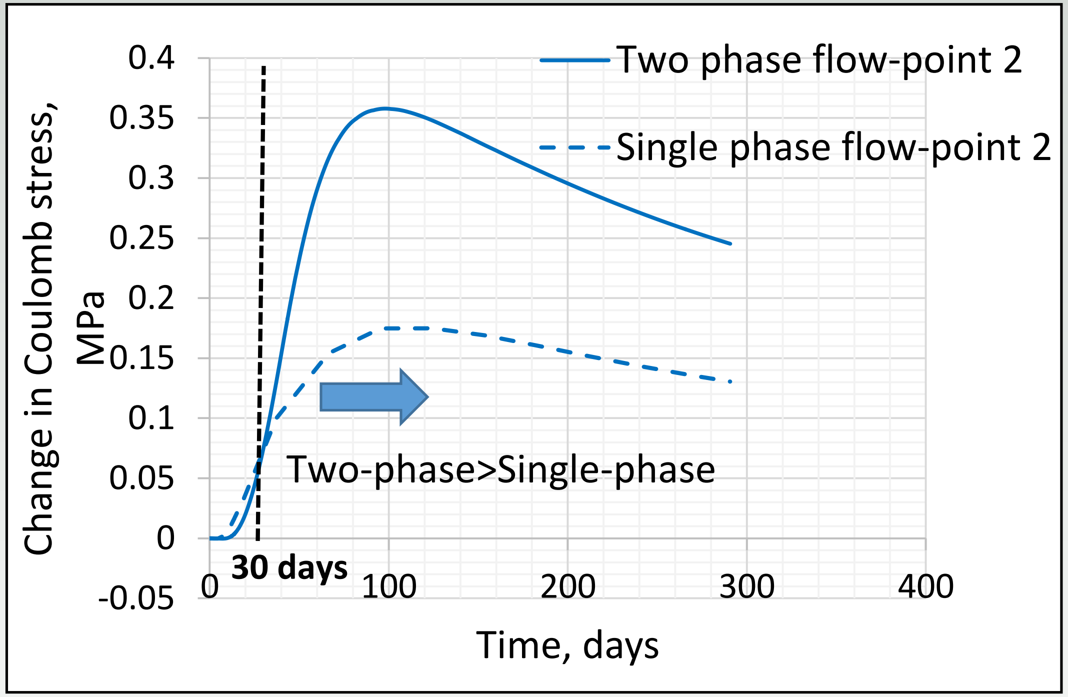




- **Pore pressure at point 3 is lower than that at point 2**
- **Coulomb stress at point 3 is higher than that at point 2 causing higher chances of failure in basement**

# Coulomb stress changes at Point 2 in faults

$$Coulomb\ stress, \Delta\tau = \Delta\tau_s + f(\Delta\sigma_n + \Delta p_f)$$



- **Discrepancy in the coulomb stress can be more than 100%**
- **Single phase flow condition can underestimate slip-induced failure in faults**

# Conclusions

- Under single phase flow condition pore pressure buildup is lower which underestimate the chances of fault failure

- Based on analysis of coulomb stress, faults are more likely to slip at the basement vs inside the formation

- Positive shear stress develops in faults which cause faulting and negative shear stress develops in saline aquifer which inhibits faulting

# Thanks