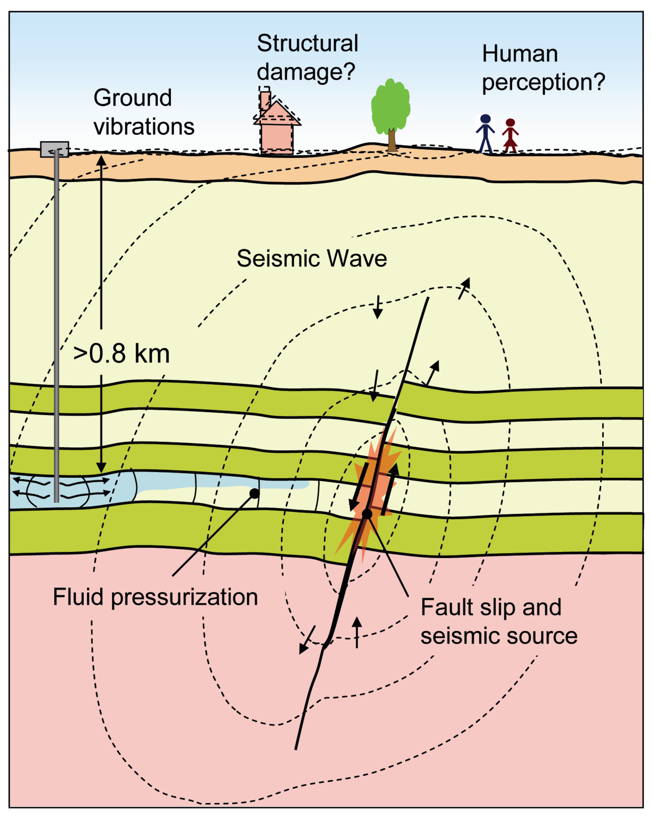
3D modeling of fault reactivation during CO_2 injection

Rinaldi, A. P., Vilarrasa, V., Rutqvist, J., Cappa, F.

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service
ETH zürich
10. - 13. March 2015 DAVOS SCHATZALP Induced Seismicity Workshop
BERKELEY LAB

Introduction

Geological carbon sequestration considered a feasible solution but the overpressure due to large-scale fluid injection may induce seismic events.



Previous 2D model:

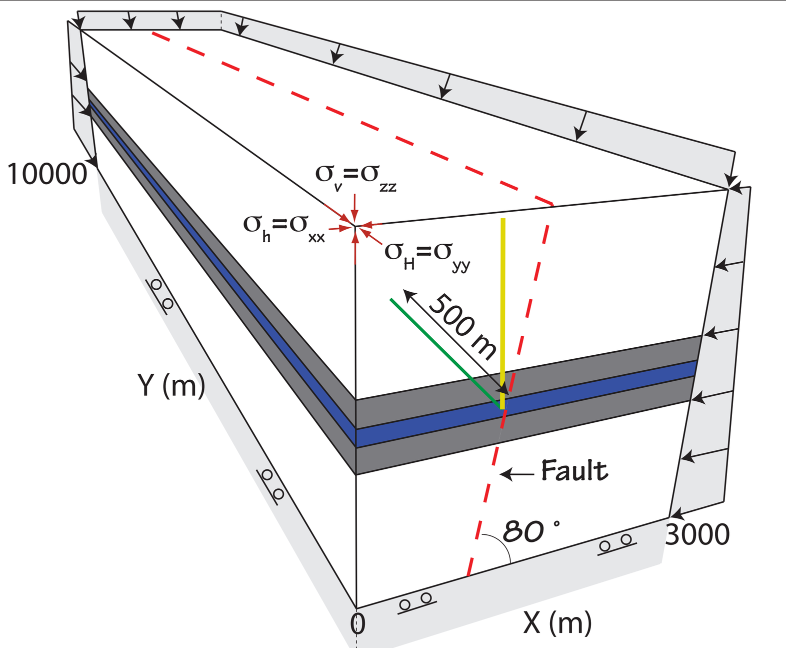
- CO_2 injection can cause seismicity (depending on injection rate and initial fault permeability)
- Reactivation may increase CO_2 leakage (but not necessarily)
- Fault and site architecture play a role (e.g. seismicity and leakage affected by size of caprock and/or reservoir)
- Low potential for structural damage

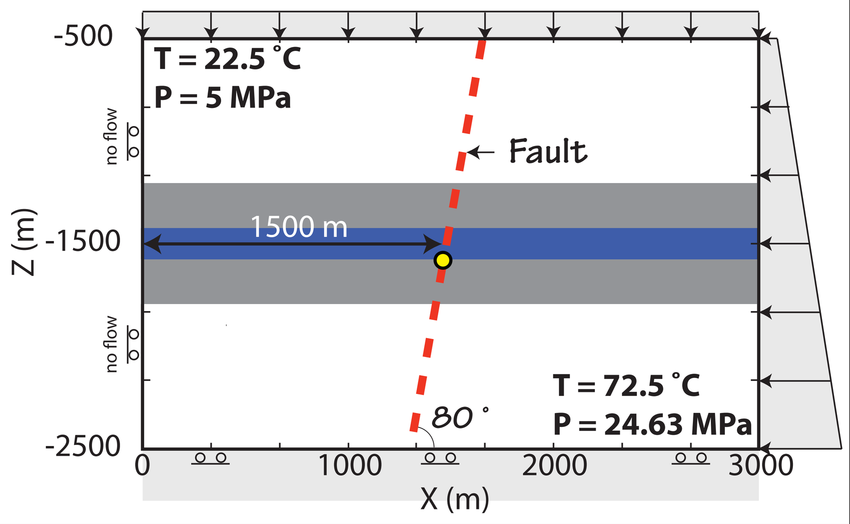
What will change if we account for a full 3D model?

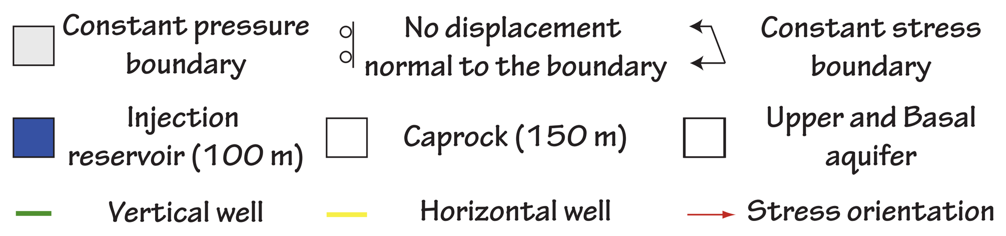
Modeling setup

- TOUGH-FLAC/ECO2N
  Fully hydro-mechanical coupling
- 100 m storage aquifer, bounded by 150 m caprock
- Pre-existing normal fault with dip 80°
- CO_2 injection at -1500 m, 1500 m from the fault: 120 kg/s for a 5 years injection period
- Isothermal with gradient 25°C/km
- Initial hydrostatic linear gradient
- Constant pressure and stress boundary
- Extensional stress regime:

$$\sigma_H = \sigma_h = 0.7\ \sigma_V$$

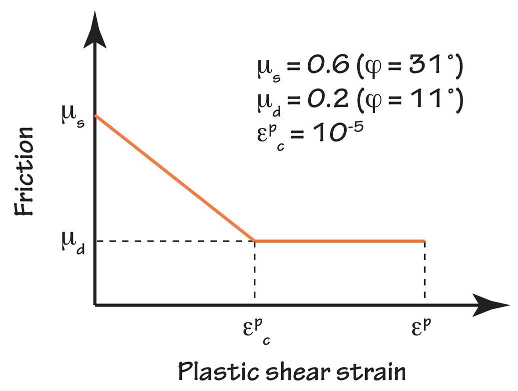




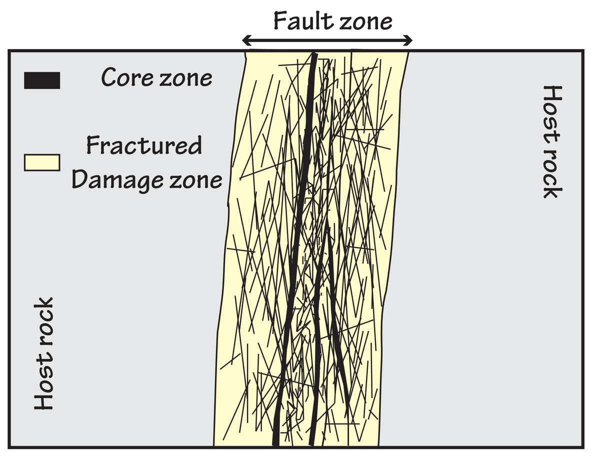


Geomechanics and fluid flow coupling

- Damage zone as high permeability zone
- Fault core with Ubiquitous-joint model (oriented weak plane in a Mohr-Coulomb solid)
- Strain-softening model: friction as function of plastic shear strain



Damage zone: 10^{-15} m²
porosity as function of mean effective stress (σ'_M), permeability depends on porosity changes (Davies and Davies, 2001)



$$\phi_{hm} = (\phi_0 - \phi_r)\exp\left(5\cdot10^{-8}\Delta\sigma'_M\right) + \phi_r$$

$$\kappa_{hm} = \kappa_0 \exp\left[22.2\left(\frac{\phi_{hm}}{\phi_0} - 1\right)\right]$$

Fault core: 10^{-17} m²
Anisotropic coupling. Hydraulic parameters depend on anisotropic elasto-plastic properties. Porosity as function of plastic tensile (e_{ftp}) and shear strain (e_{fsp}), and dilation (ψ). Permeability as function of normal effective stress (σ'_n) and porosity changes (Hsiung et al., 2005). *a* and *c* empirical constants for normal-closure hyperbola (Bandis et al. ,1983)

$$\phi_{hm} = \phi_0 + \Delta\phi_{fp}$$

$$\Delta\phi_{fp} = e_{ftp} + e_{fsp}\tan\psi$$

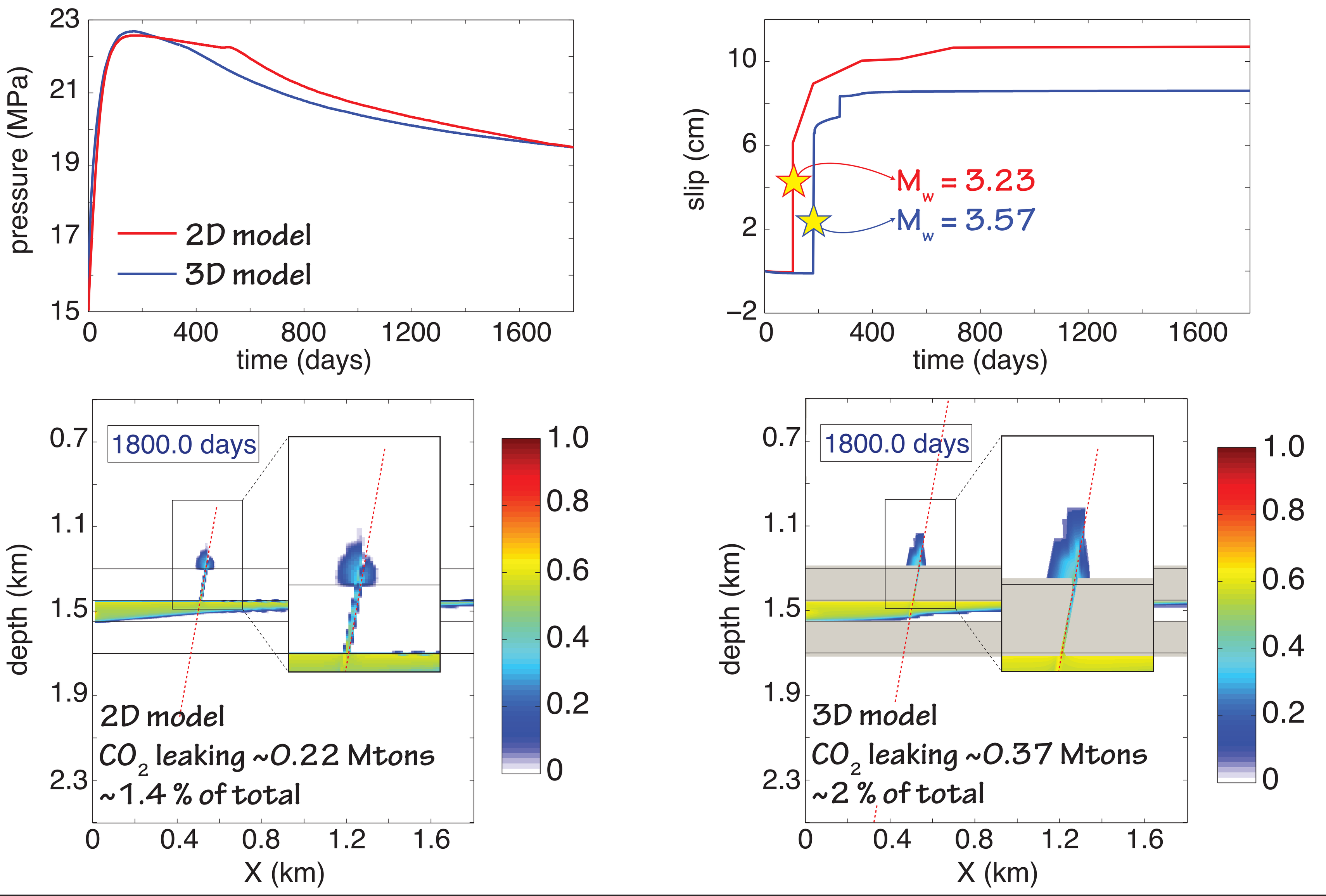
$$\kappa_{hm} = \kappa_0\left[\frac{a}{c(c\sigma'_n + 1)}\sqrt{\frac{\phi_0}{12\kappa_0}} + \frac{e_{ftp} + e_{fsp}\tan\psi}{\phi_0}\right]^3$$

$$a = K^{-1}$$

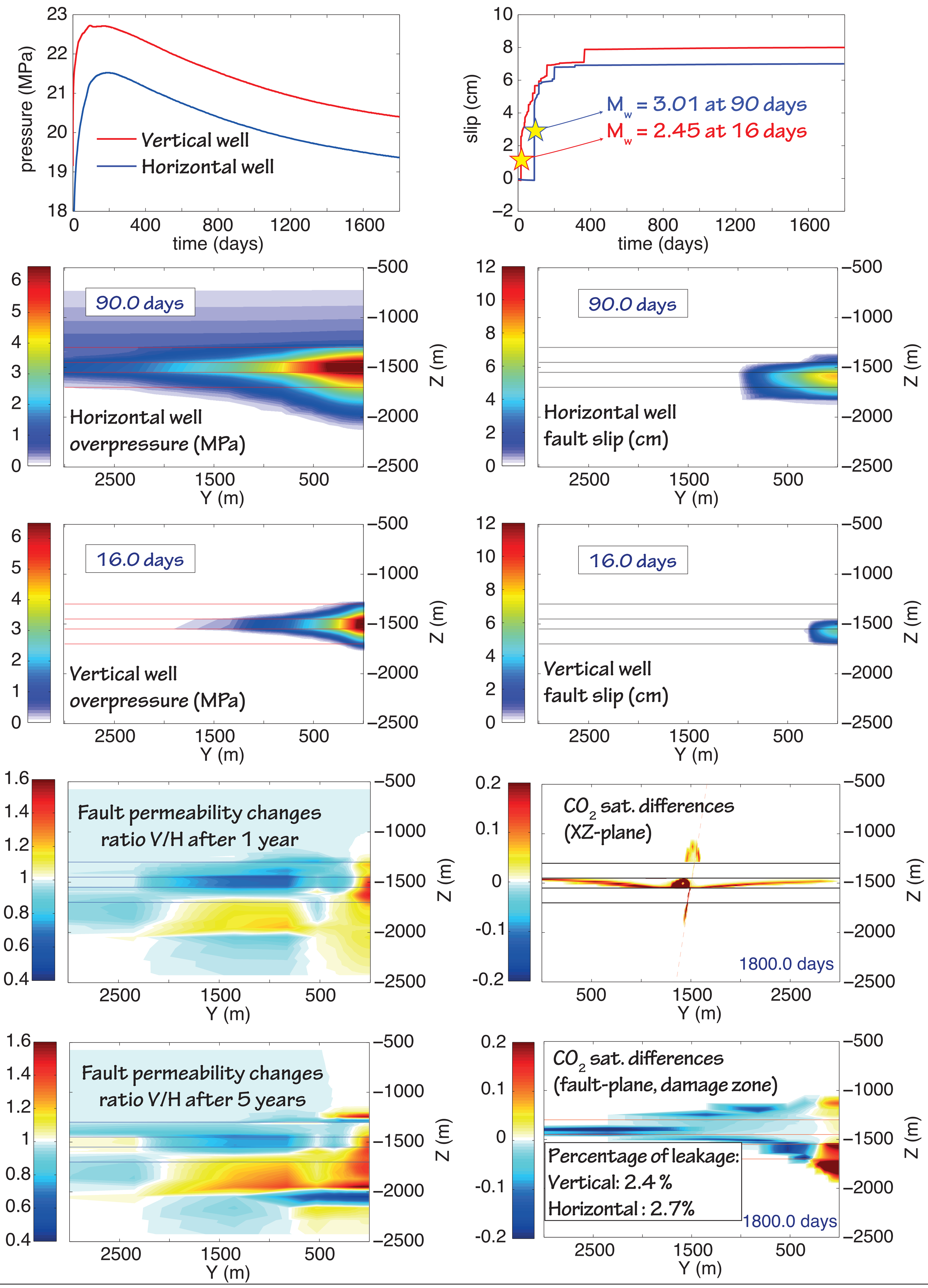
$$c = \frac{-1 \pm \sqrt{1 + 4\sigma'_n a\sqrt{\frac{\phi_0}{12\kappa_0}}}}{2\sigma'_{n0}}$$

2D vs 3D

- 2D MODEL: Injection rate 0.05 kg/s/m ➔ 0.05×1000×2 ➔ 100 kg/s
  Reactivation at about 100 days with magnitude 3.23 (circular rupture)
  RUNNING TIME: ~4 hours
- 3D MODEL: Injection rate 30 kg/s/m ➔ 30×4 ➔ 120 kg/s
  Reactivation at about 200 days with magnitude 3.57
  RUNNING TIME: ~13 hours



Vertical well vs Horizontal well: Overpressure, induced seismicity, and leakage



Conclusion

- **Overall good agreement between 2D and 3D model**
  - In 3D model simulations higher injection rate to achieve the same pressure increase.
  - 2D model percentage of leakage of about 1.4% increases to 2% in a 3D model
  - Differences in temporal evolution because of permeability changes
- **Horizontal vs Vertical injection well**:
  - Vertical well: localized but faster pressure increase, then less slip on a smaller area.
  - Horizontal well: pressure over a larger space, longer time i to reach the critical pressurization, then larger slip on larger area.
  - For vertical well slightly higher permeability in the near-well region, for horizontal well larger permeability changes along the fault strike, and then leakage varies accordingly.