Geospatial monitoring for safe carbon storage

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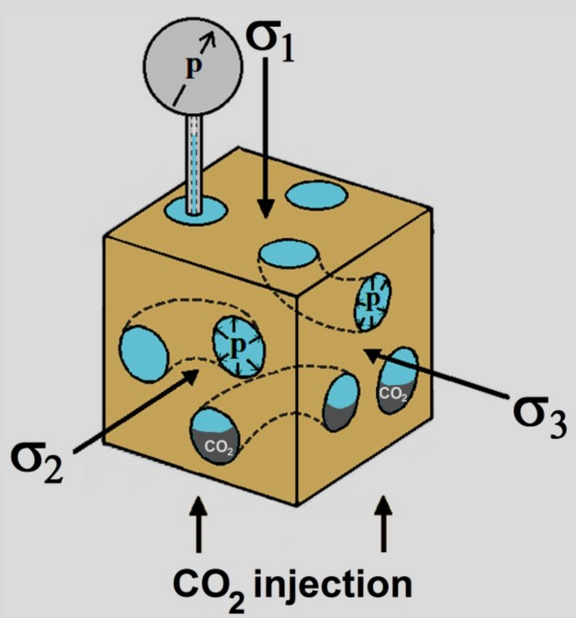
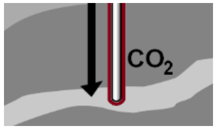
http://rockmechanics.cee.illinois.edu

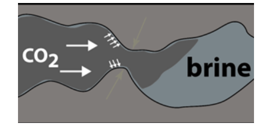


NFI meeting

September 28, 2021



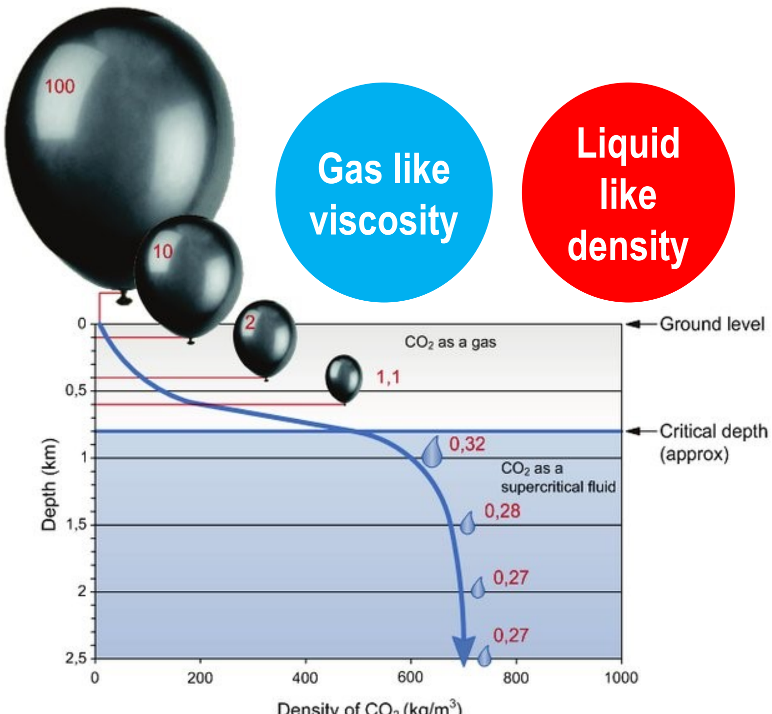
CO_2 storage



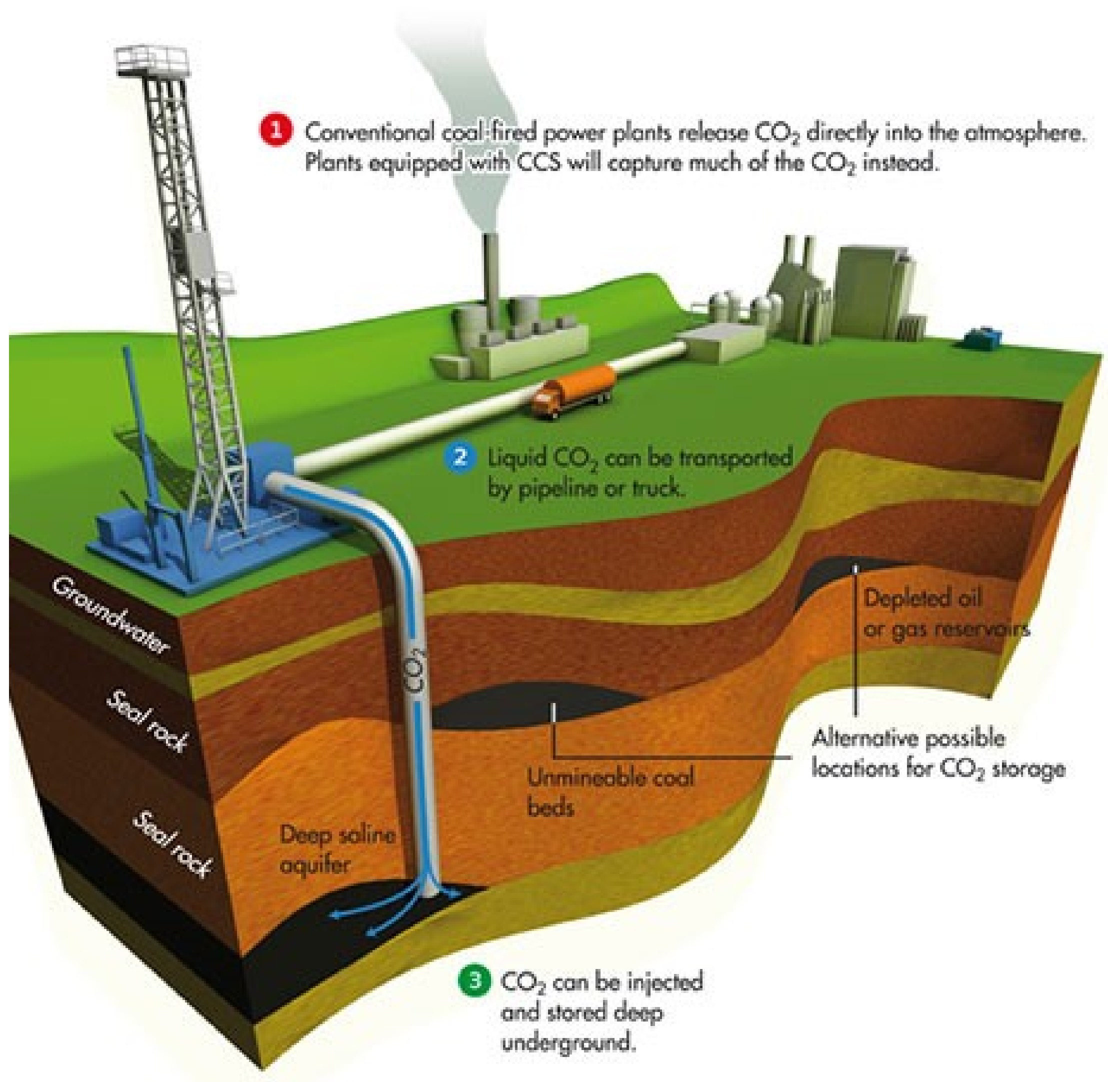
Beneath 800m underground CO_2 exists in the supercritical state: temperature > 31.1 ºC, pressure > 7.4 MPa, density > 600 kg/m^3

Gas like viscosity

Liquid like density



IEA (2010)

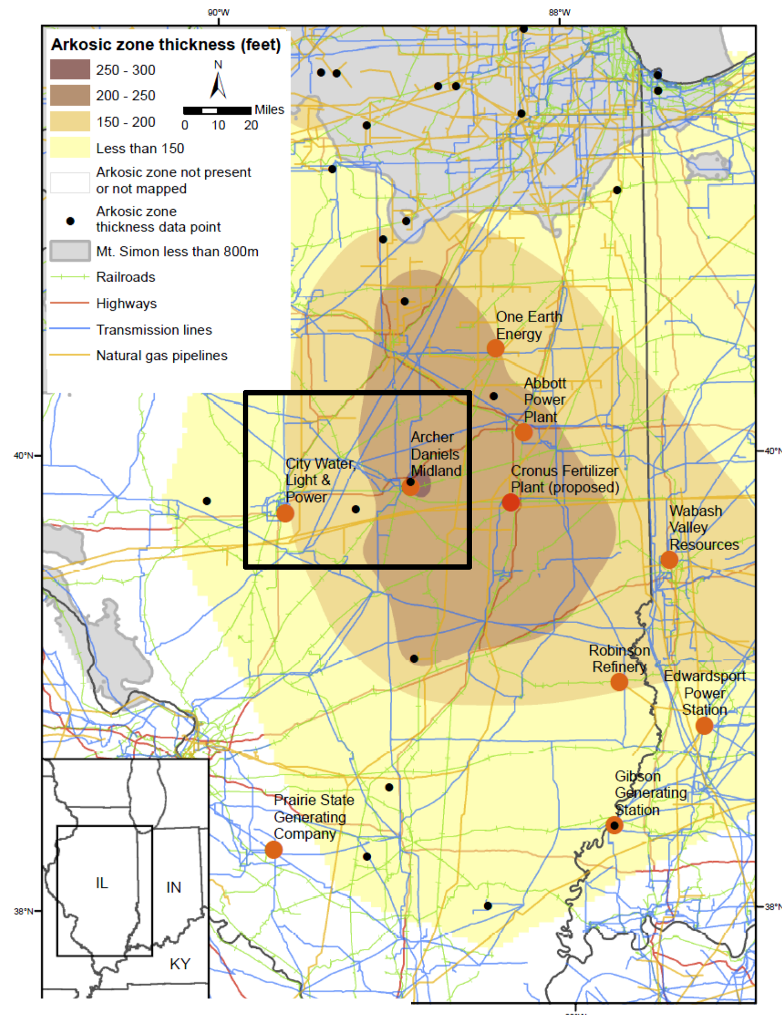


CCS in Illinois

CarbonSAFE Illinois

Commercialization

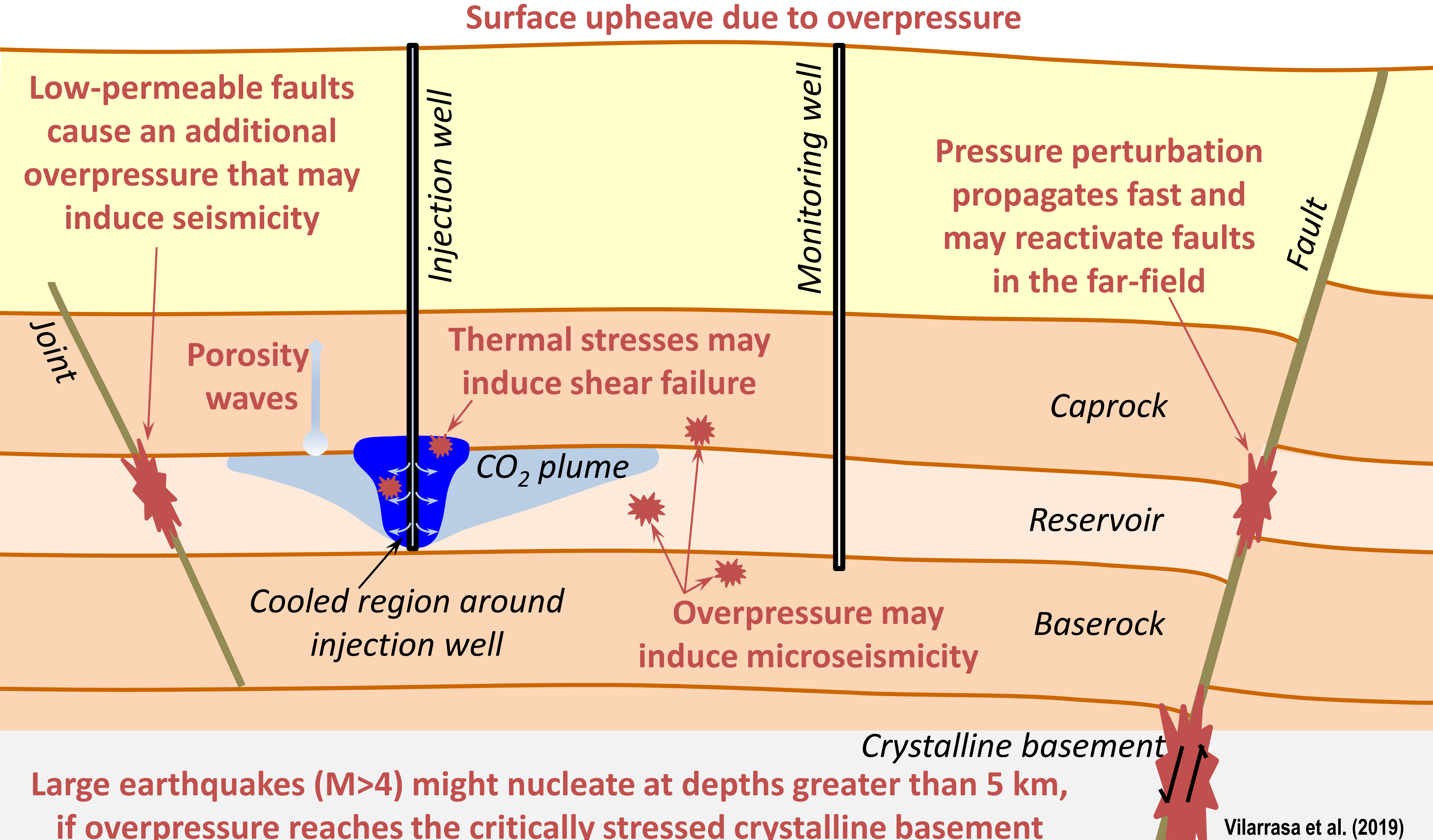
- 45Q credits give up to \$50 tax relief/ ton of stored (instead of emitted CO_2) for companies
- Storage: plants can breakeven on project costs by capturing and injecting at least 250 kilotons/year
- Utilization: plants must capture at least 360 kilotons/year to breakeven – but additional costs (transport) likely needed
- Storage potential: injection of over 50Mt CO_2 over 30 years can be performed



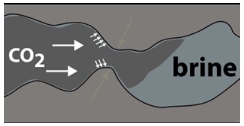
ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE

CarbonSAFE Illinois

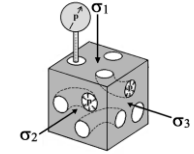
Challenges of CO_2 storage



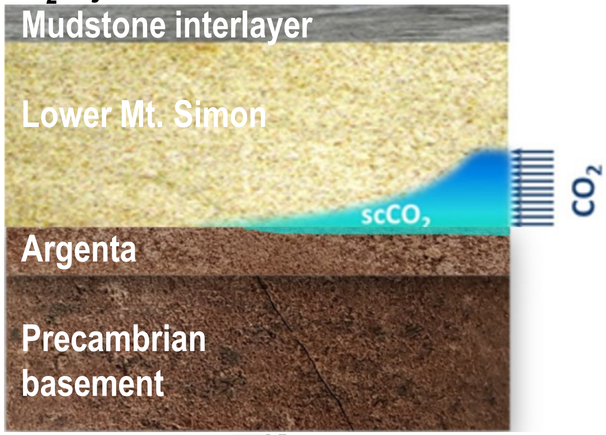
Vilarrasa et al. (2019)



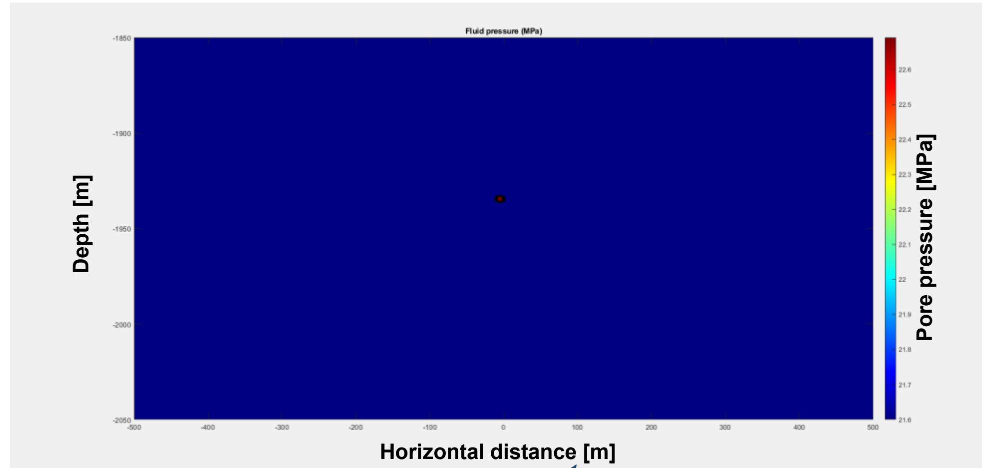
Simulation of Illinois Basin response



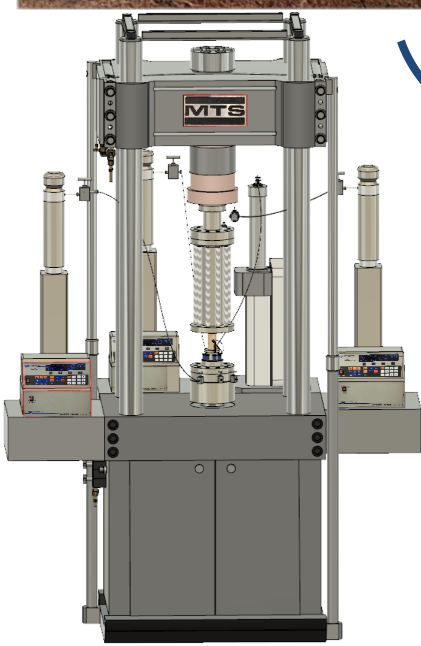
CO_2 injection in Illinois Basin model



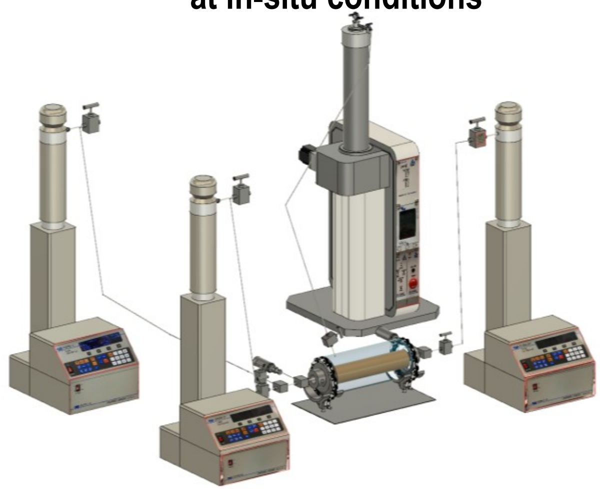
Numerical modeling of reservoir behavior



Laboratory characterization of rock properties at in-situ conditions

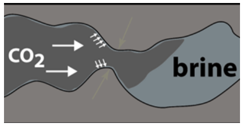


Triaxial compression

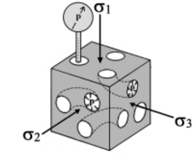


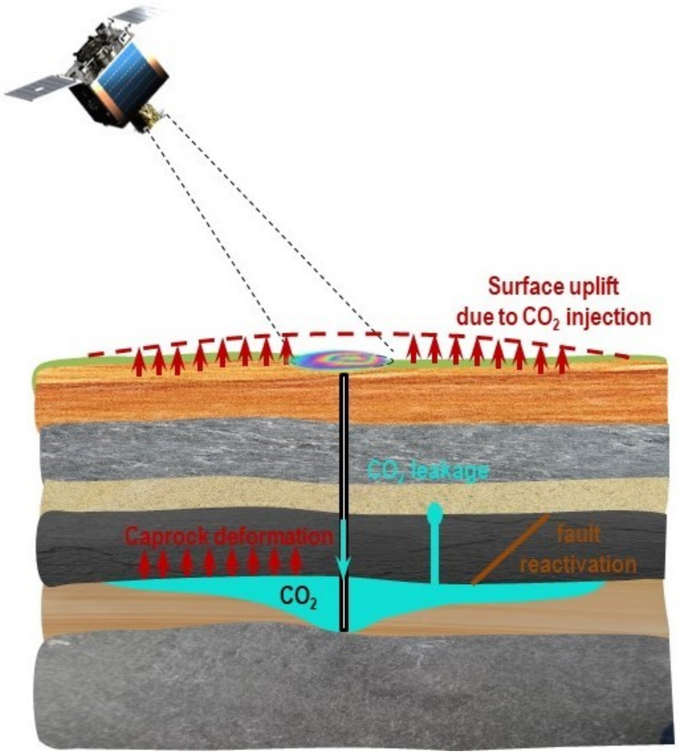
Core flooding

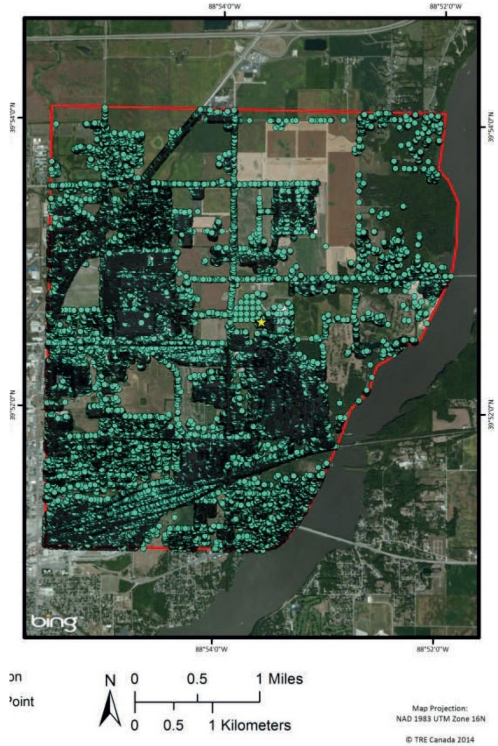
Hydrostatic compression



Geospatial monitoring

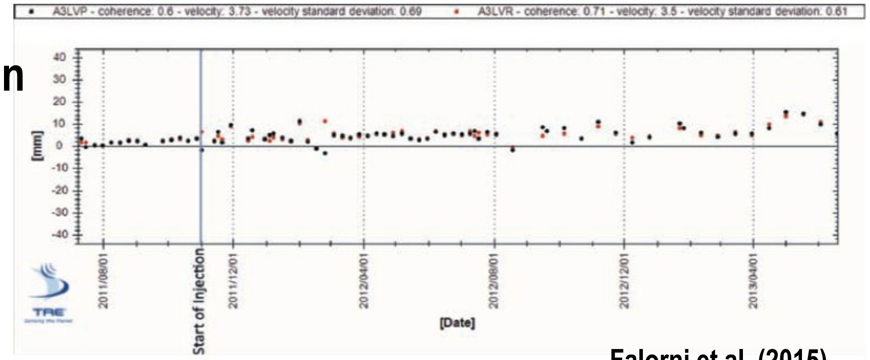




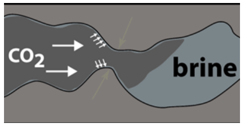


Geospatial monitoring of Decatur project in Illinois Basin indicated surface uplift of 8 mm over the 3 years of continuous injection.

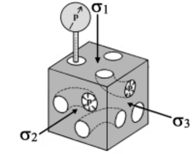
- Geospatial monitoring can provide information on CO_2 injection associated surface uplift
- CO_2 plume location ad discontinuities can be located



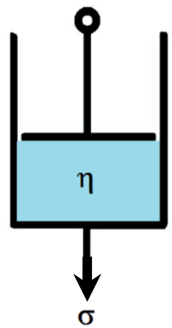
Falorni et al. (2015)



Constitutive model

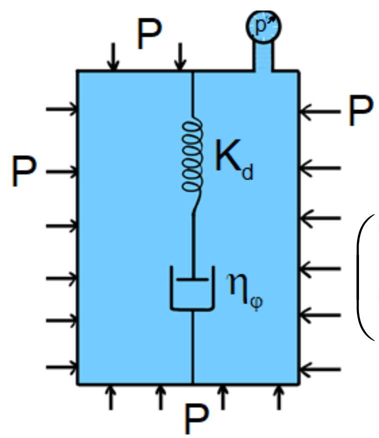


σ – applied stress
$\dot{\varepsilon}$ – strain rate
η – viscosity



- **Time-dependent deformation could be captured by introducing viscous element.**
- **Magnitude of strain rate is proportional to applied mean stress.**
- **Coefficient of proportionality is bulk viscosity η_ϕ [Pa·s].**

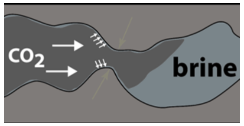
P – Total mean stress
p^f – Pore pressure
K_d – Drained bulk modulus
B – Skempton's coefficient
α – Biot coefficient
η_ϕ – Bulk viscosity
ϕ – Porosity
q_k – k component of specific discharge vector
v^s_k – k component of solid particles velocity vector



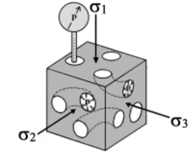
Elastic term | Viscous term

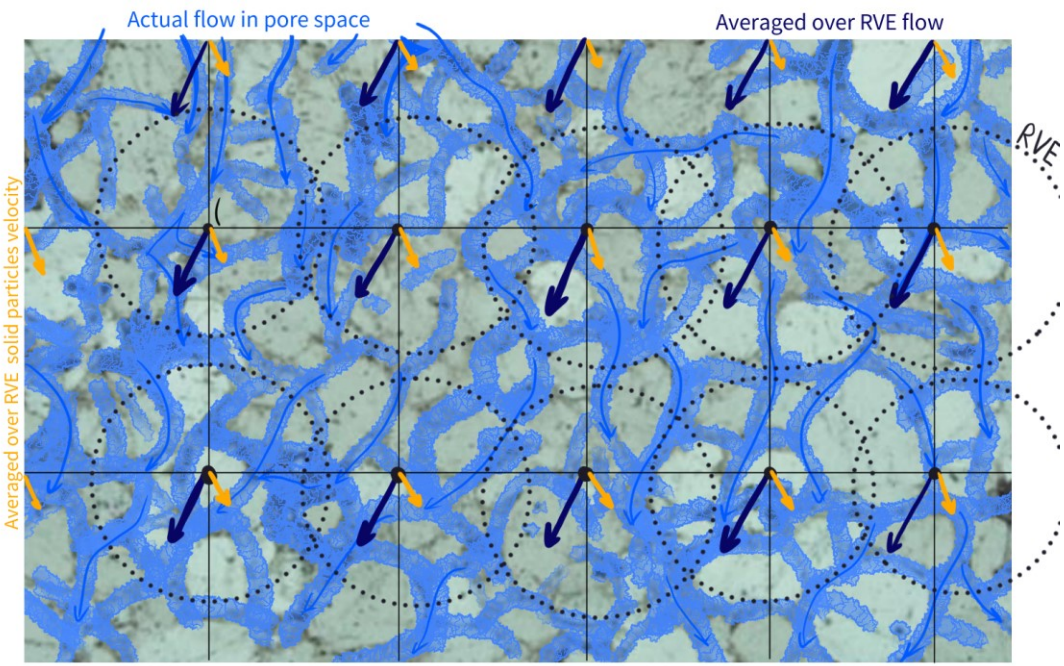
$$\begin{pmatrix}\nabla_k\cdot v_k^s\\ \nabla_k\cdot q_k\end{pmatrix} = -\frac{1}{K_d}\begin{pmatrix}1 & -\alpha\\ -\alpha & \frac{\alpha}{B}\end{pmatrix}\begin{pmatrix}\frac{dP}{dt}\\ \frac{dp^f}{dt}\end{pmatrix} + \begin{pmatrix}\frac{P-p^f}{(1-\phi)\eta_\phi}\\ -\frac{P-p^f}{(1-\phi)\eta_\phi}\end{pmatrix}$$

Yarushina and Podladchikov (2015)



Modeling of coupled injection process





Biot's equations for volumetric part of stress tensor

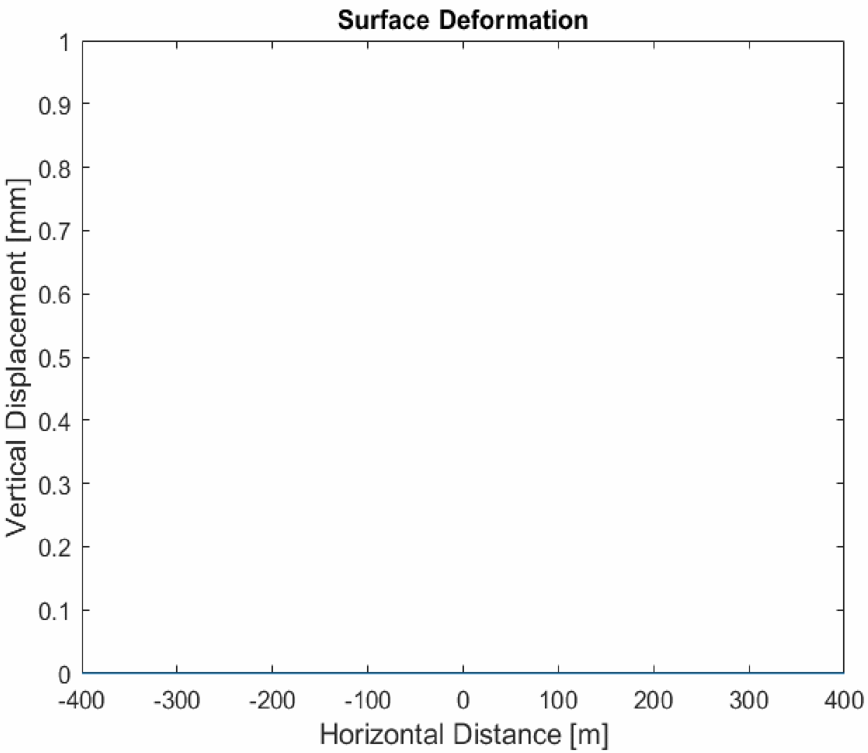
$$\begin{pmatrix} \dfrac{dP}{dt} \\ \dfrac{dp^f}{dt} \end{pmatrix} = -K_u \begin{pmatrix} 1 & B \\ B & \dfrac{B}{\alpha} \end{pmatrix} \begin{pmatrix} \nabla_k \cdot q_k \\ \nabla_k \cdot v_k^s \end{pmatrix}$$

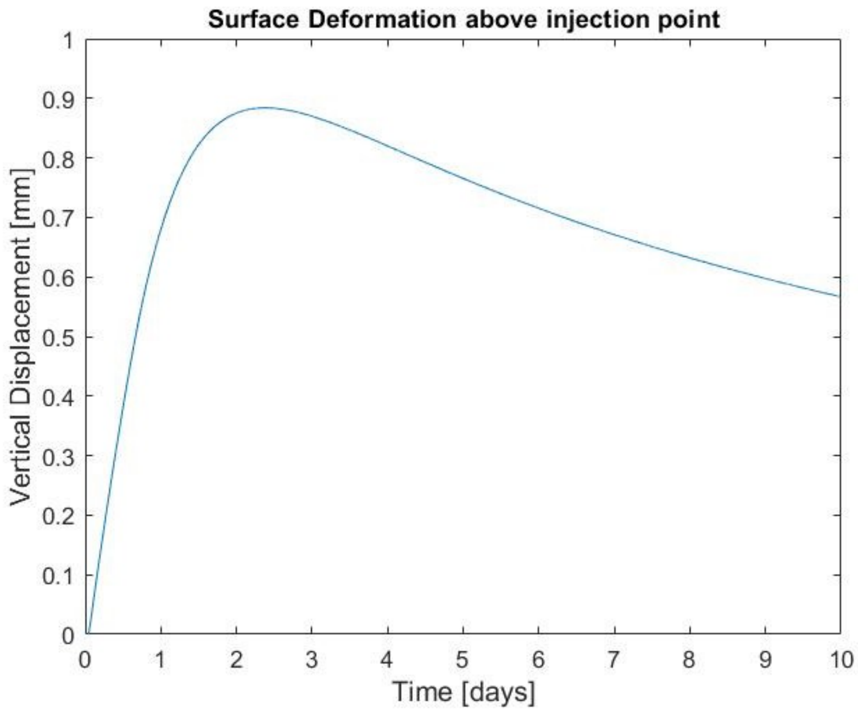
Conservation of linear momentum

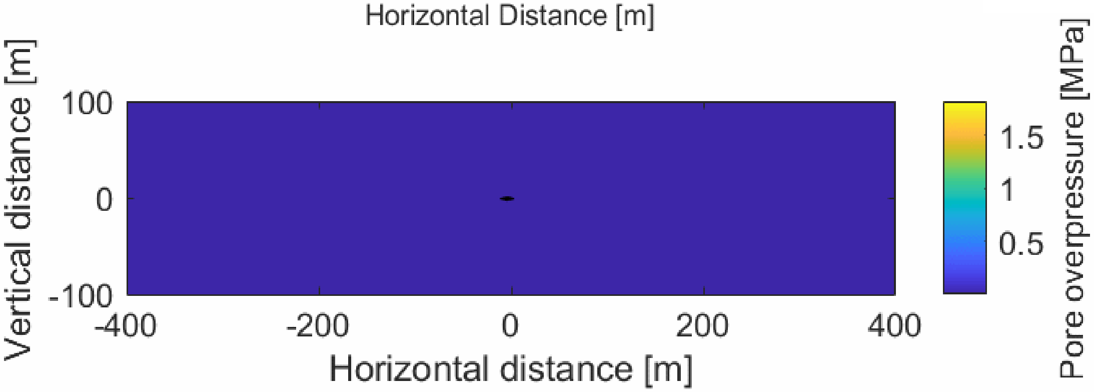
$$\begin{pmatrix} \nabla_j(-P\delta_{ij} + \tau_{ij}) \\ \dfrac{\eta_f}{k} q_k + \nabla_k p^f \end{pmatrix} = \begin{pmatrix} \rho_t & -\rho_f \\ -\rho_f & \rho_a \end{pmatrix} \begin{pmatrix} \dfrac{\partial v_k^s}{\partial t} \\ -\dfrac{\partial q_k}{\partial t} \end{pmatrix}$$

Measured properties will are implemented in the numerical code, which will predict surface uplift considering hydro-mechanical coupling and the material properties.

Preliminary Results

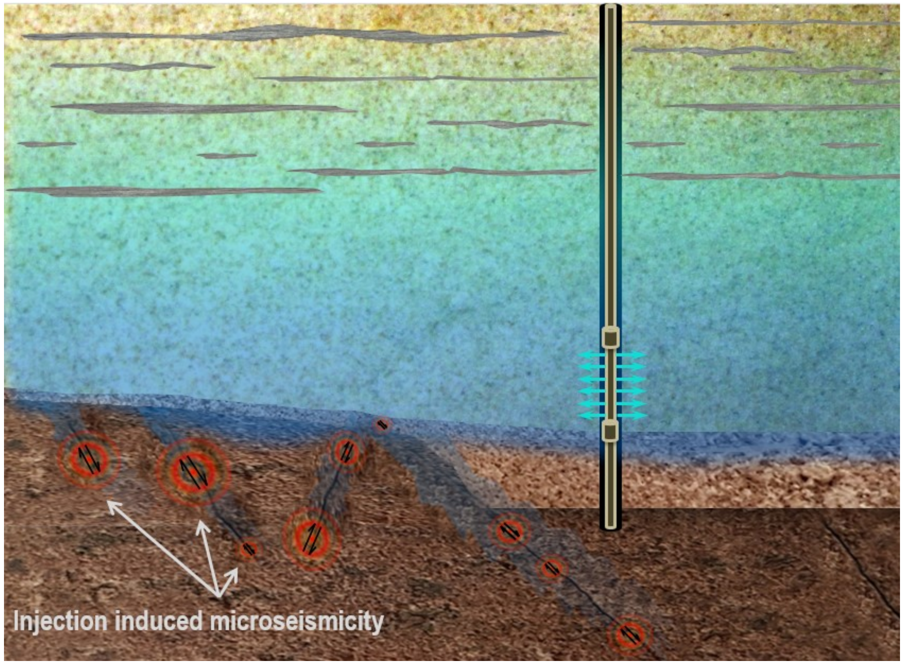


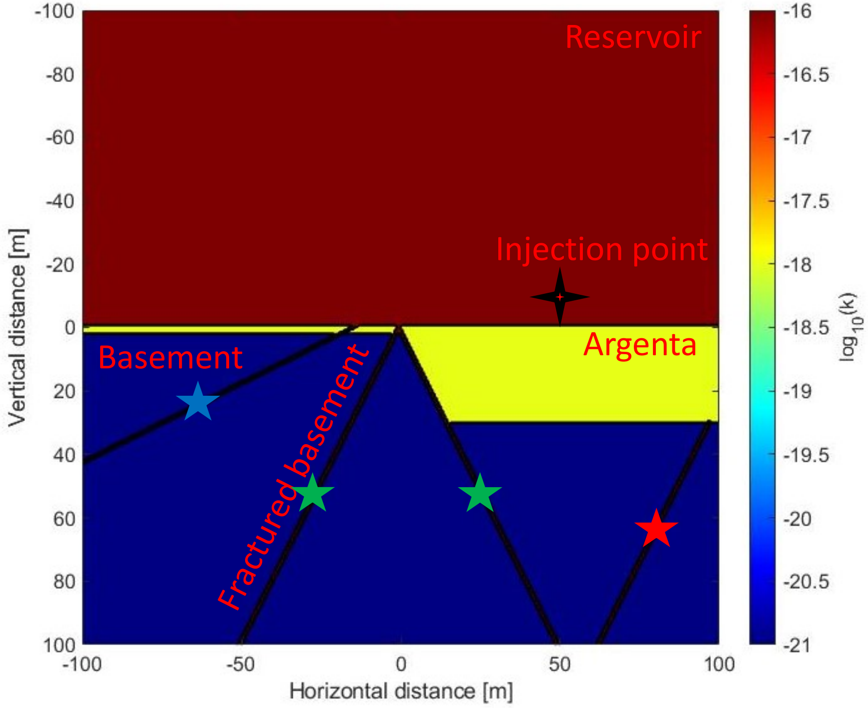


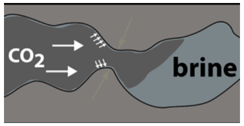


Expansion of the model

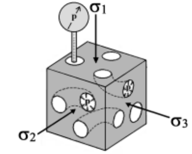
- Four materials are considered: Mt. Simon, Argenta, intact and fractured Precambrian rhyolite.
- Three faults in the basement have hydraulic connection to the reservoir.







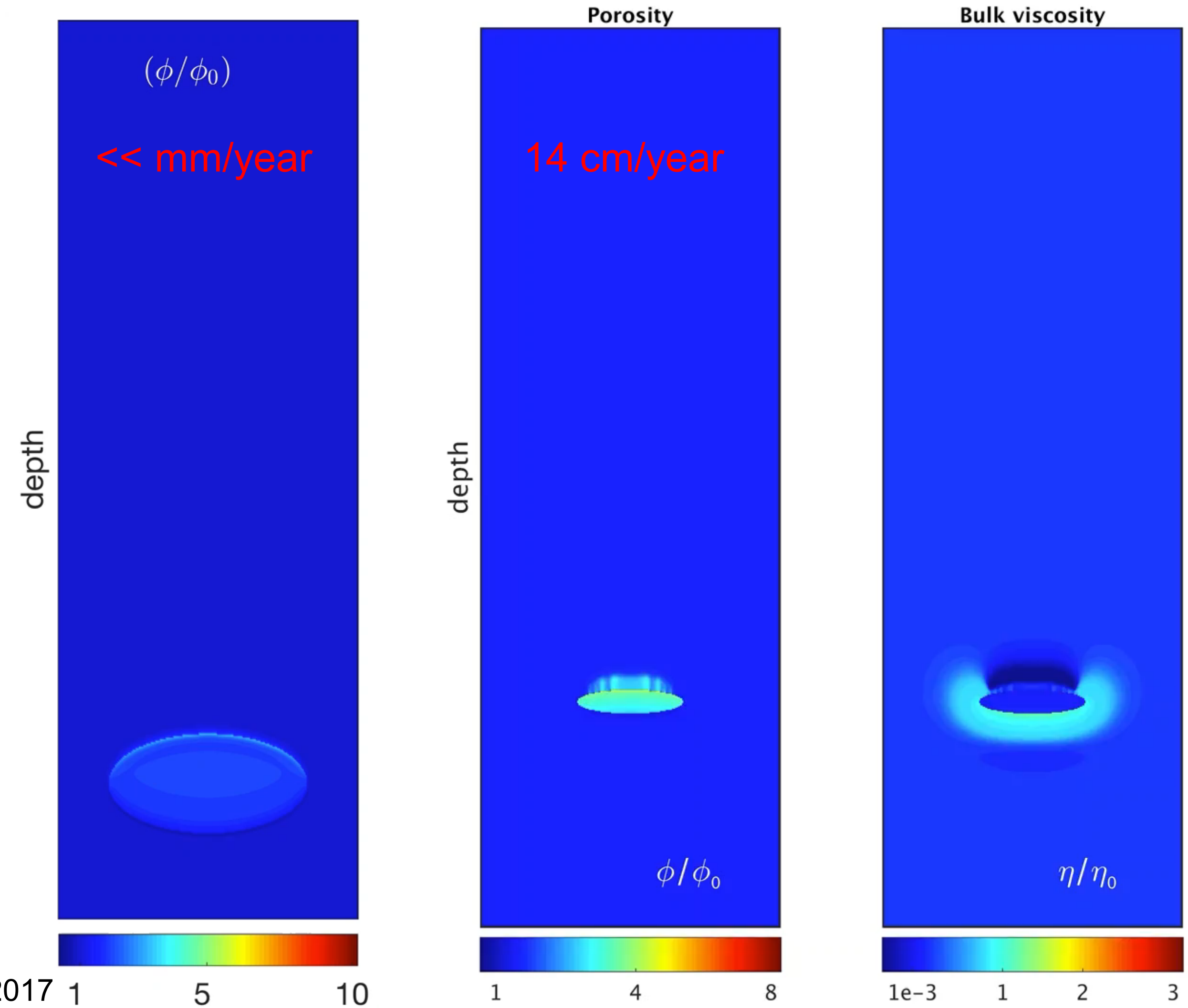
2D flow in shaly caprock



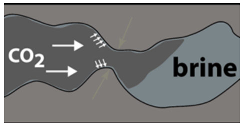
Without lab rheology: blobs **With lab rheology: channels**

- **Buoyancy driven flow**
- **Compaction of the sample under gravity**
- **High porosity anomaly**

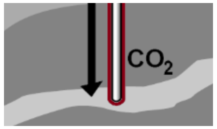
Fully coupled 2D
Hydro-Mechanical simulation
255x767 grid points
1200 physical time steps

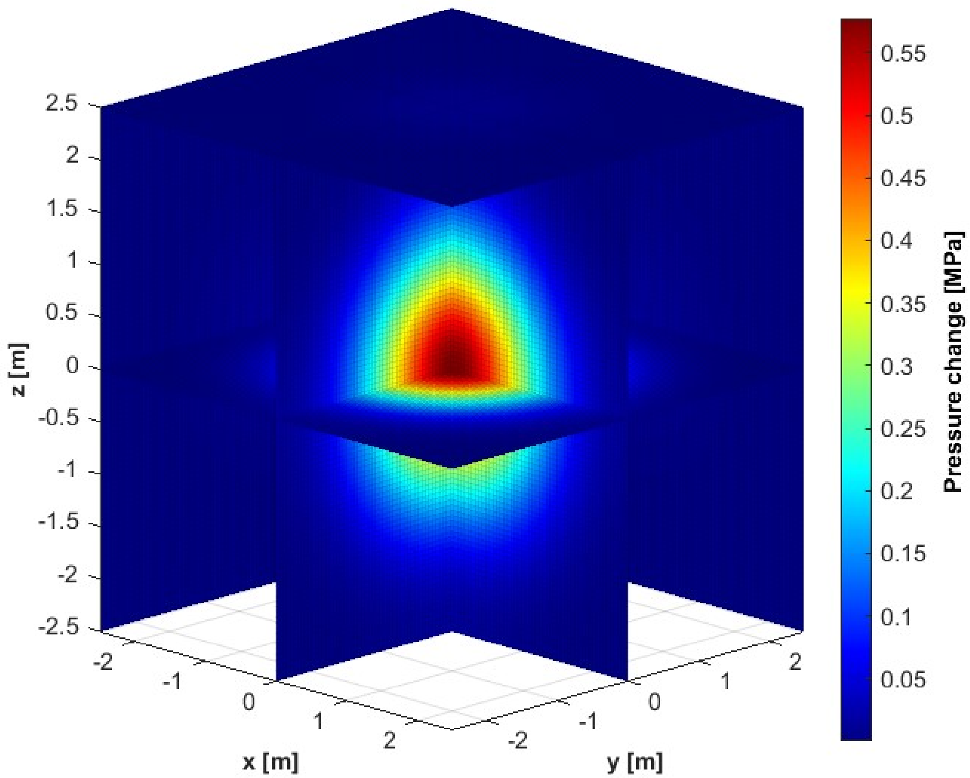


Räss Makhnenko Podladchikov Laloui, 2017



3D fully coupled models





$$\begin{pmatrix} \nabla_k v_k^s \\ \nabla_k q_k^D \\ \nabla_k q_k^T \end{pmatrix} = \begin{pmatrix} \dfrac{1}{K_d} & -\dfrac{\alpha}{K_d} & -\alpha_T \\ -\dfrac{\alpha}{K_d} & \dfrac{\alpha}{BK_d} & \alpha_{Tf} \\ -\alpha_T & \alpha_{Tf} & \rho c_p \end{pmatrix} \begin{pmatrix} \partial P / \partial t \\ \partial p^f / \partial t \\ \partial T / \partial t \end{pmatrix}$$

- Solution of 21 differential equations in each grid point.

- High resolution numerical grid 500·500·1000 requires solving ~10^9 equations for each time step.

- According to fluid diffusion processes – each time step should be on the order of seconds.

- Needs supercomputers to solve the full set of coupled equations and predict surface uplift

- Can use surface uplift to modify the model and predict location of CO_2 plume and faults