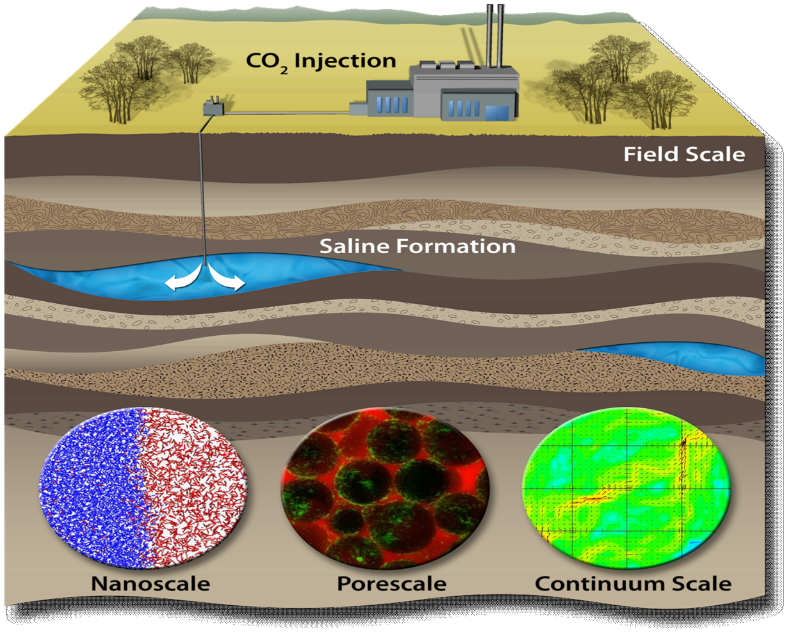
SAND2017-2249PE

Coupled Multi-Physics Analysis of Caprock Integrity and Joint Reactivation During CO_2 Sequestration



Pania Newell

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SIAM-Annual meeting 2014

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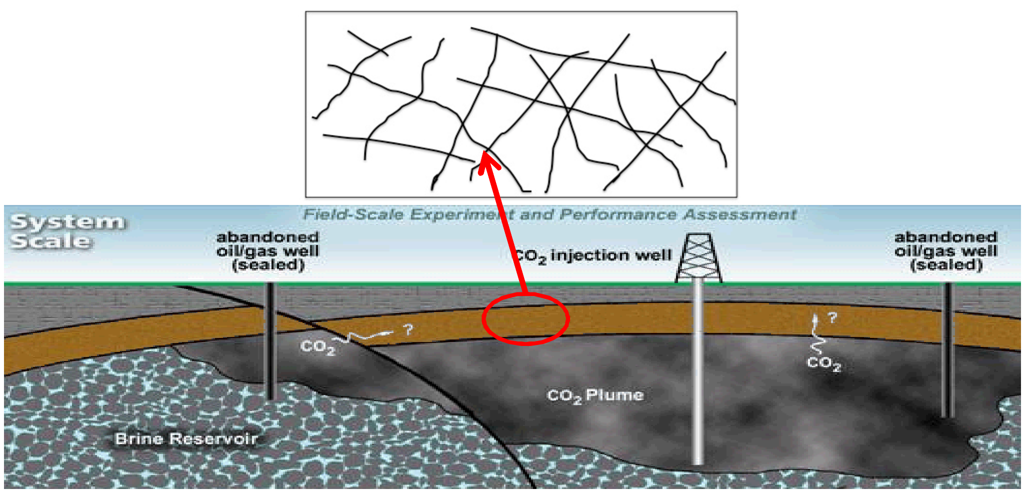
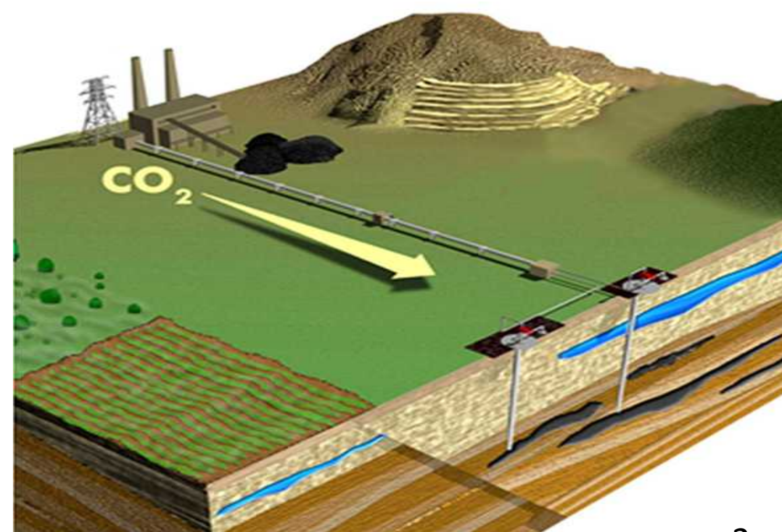
CO_2 Sequestration

- Global consumption of fossil fuels has significantly increased levels of atmospheric CO_2, a greenhouse gas.
- Carbon capture and storage (CCS) is a promising mitigation strategy.
- Sealing ability of the overlying caprock is one of the most important determining factors related to its storage effectiveness over geological times.





Ref: DOE-NETL

Numerical model

- Fluid:
  - Two phase, immiscible flow
  - The pore space is saturated
  - Capillary pressure is so small
  - No mass transfer between phases
- Mass balance equation

$$\frac{\partial(\rho_w \phi S_w)}{\partial t} = \nabla.(\rho_w \frac{k_{rw}}{\mu_w} k \bullet (\nabla p - \rho_w g) + Q_w$$

$$\frac{\partial(\rho_n \phi S_n)}{\partial t} = \nabla.(\rho_w \frac{k_{rn}}{\mu_n} k \bullet (\nabla p + \nabla p_c - \rho_n g) + Q_n$$

$$p_c = p_n - p_w$$

$$S_w + S_n = 1$$

Numerical model

- Solid:
  - Quasi static
  - Linear elastic

$$\Delta.\sigma + \rho g = 0$$

$$\sigma = \lambda tr(\epsilon) I + 2G\epsilon$$

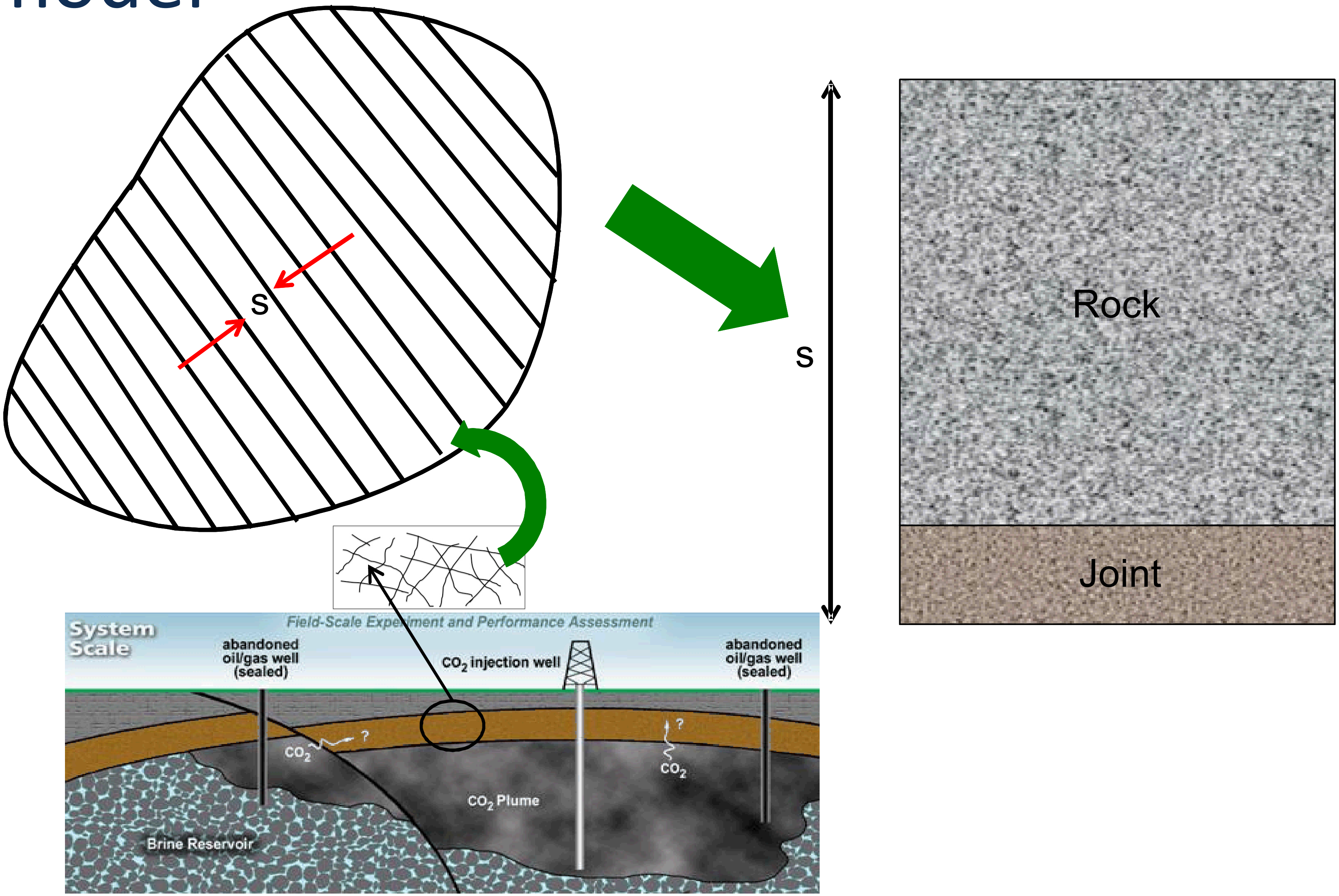
$$\epsilon = \frac{1}{2}[\Delta u + (\Delta u)^T]$$

- Coupling:

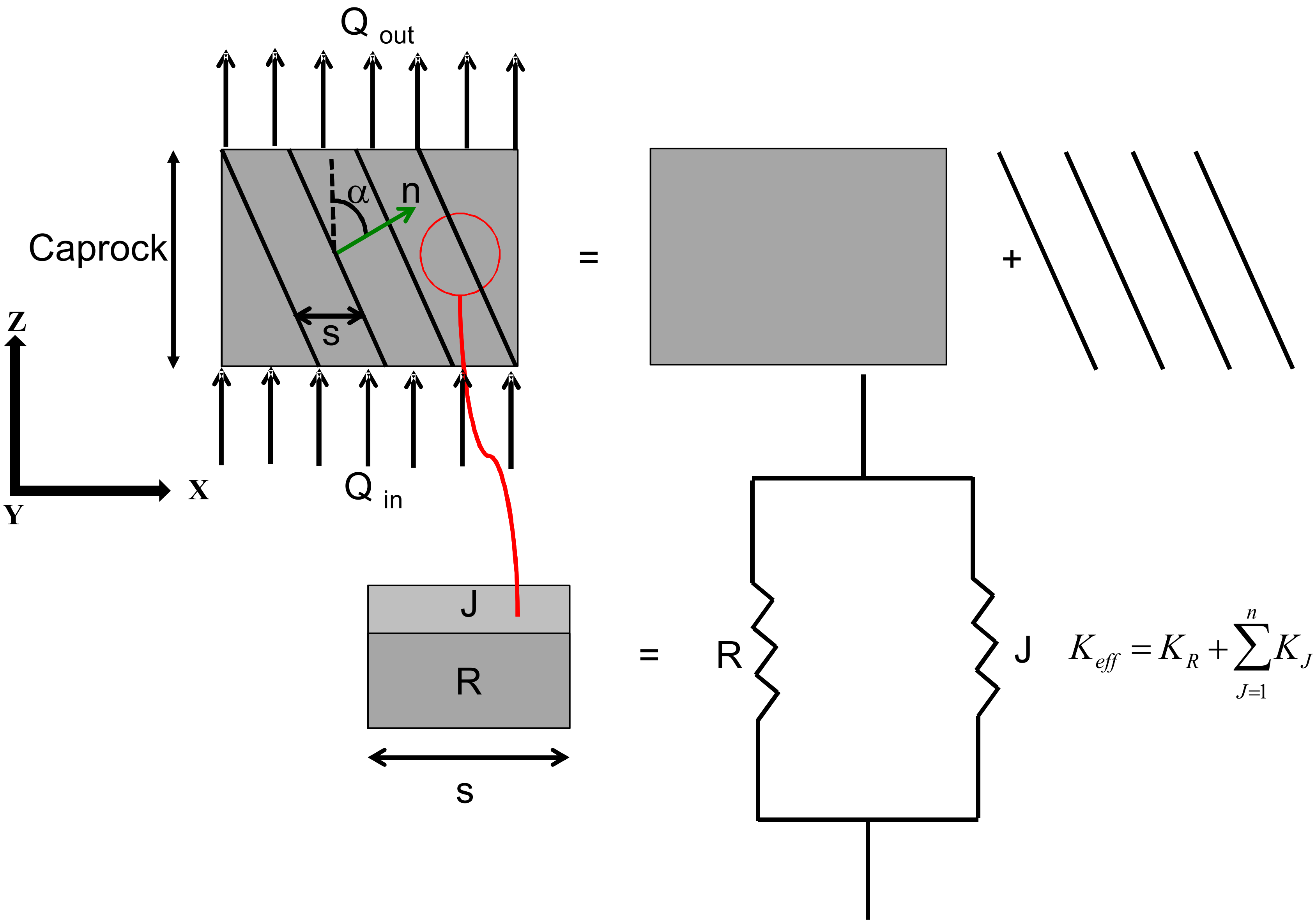
$$\sigma_{eff} = \sigma + \alpha I p$$

$$\lambda = \lambda(\sigma_{eff})$$

Equivalent continuum model-Geo model



Joint modeling



$$K_{eff} = K_R + \sum_{J=1}^{n} K_J$$

Formulation

Coupling

$$K_{eff} = K_R + \sum_{J=1}^{n} K_J$$

$$n_1 = \sin\alpha \sin\beta$$

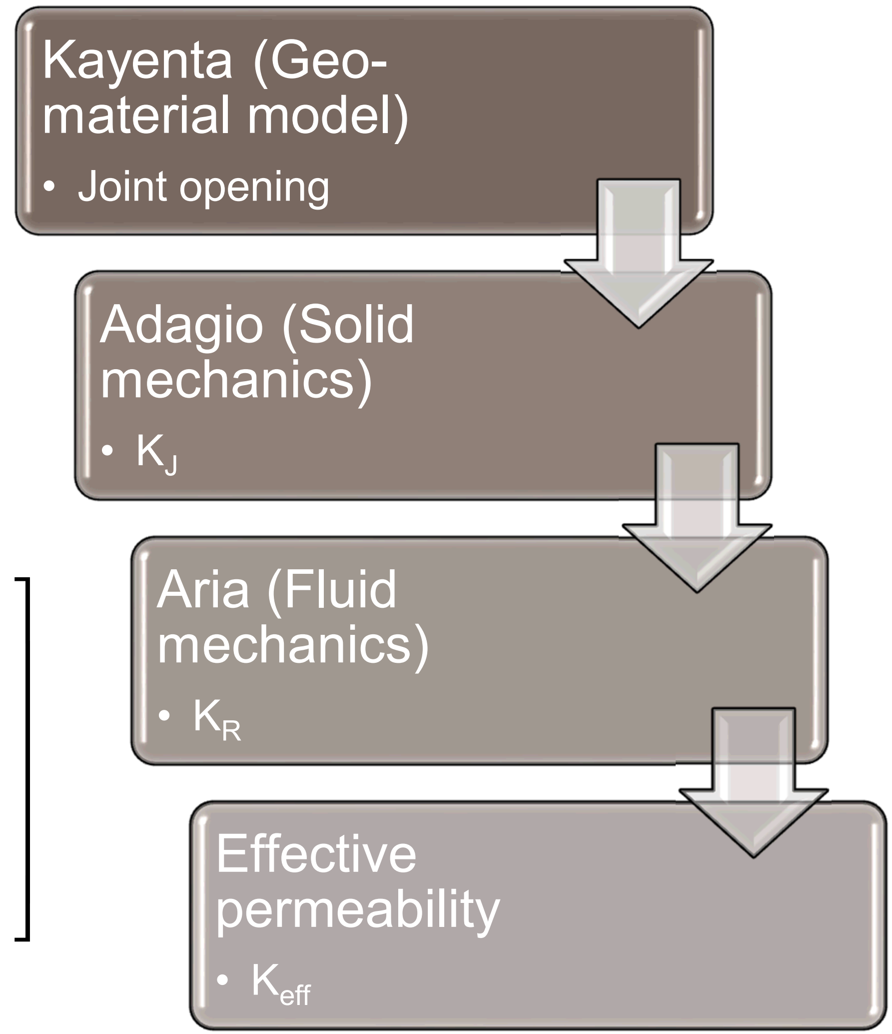
$$n_2 = \sin\alpha \cos\beta$$

$$n_3 = \cos\alpha$$

Joint opening

$$K_J = \frac{b^3}{12s} \begin{bmatrix} 1-n_1^2 & -n_1 n_2 & -n_1 n_3 \\ -n_1 n_2 & 1-n_2^2 & -n_2 n_3 \\ -n_1 n_3 & -n_2 n_3 & 1-n_3^2 \end{bmatrix}$$

Joint spacing



Formulation

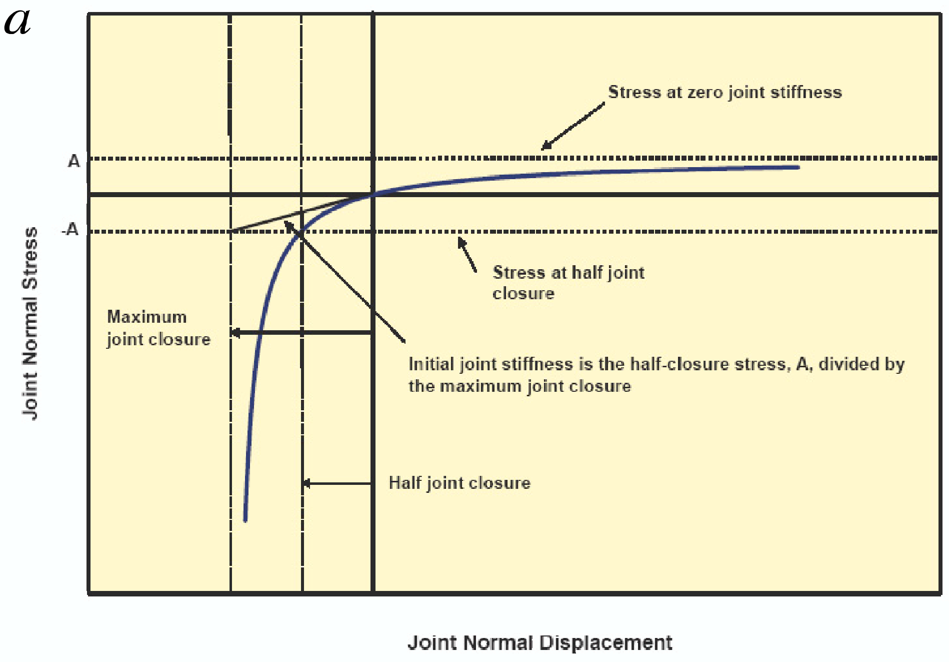
$$\sigma = \frac{\varepsilon}{A + B\varepsilon} \Rightarrow \sigma_n = \frac{U_n}{a + bU_n}$$

$$when\ \ \sigma_n \rightarrow \infty \Rightarrow U_n \rightarrow \frac{-a}{b} = V_{\max}$$

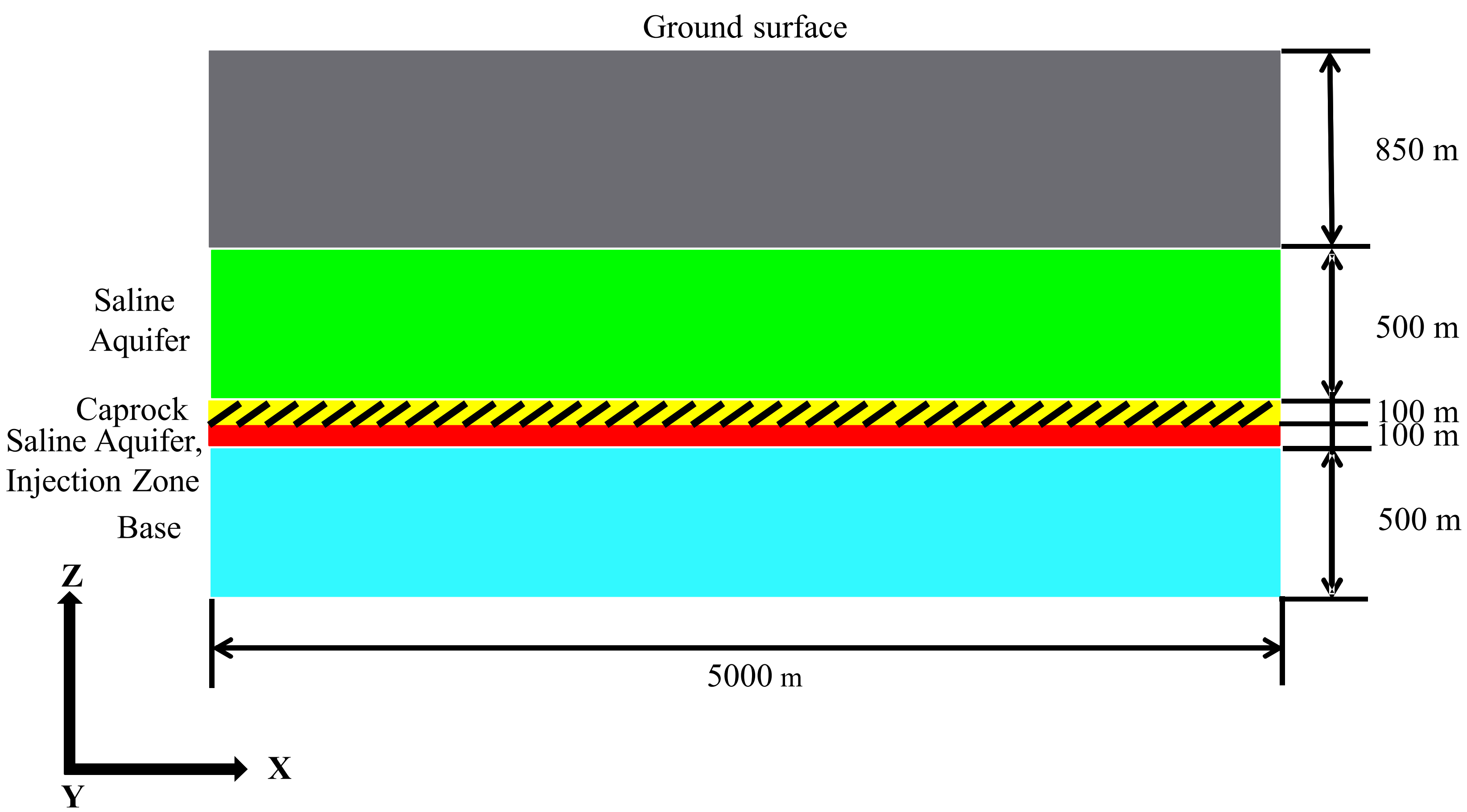
$$when\ \ \sigma_n \rightarrow 0 \Rightarrow U_n \rightarrow 0 \Rightarrow k_{ni} = \frac{1}{a}$$

$$k_n = \frac{\partial \sigma_n}{\partial U_n} \Rightarrow k_n = k_{ni}\left(1 - \frac{\sigma_n}{k_{ni}V_m}\right)^2$$

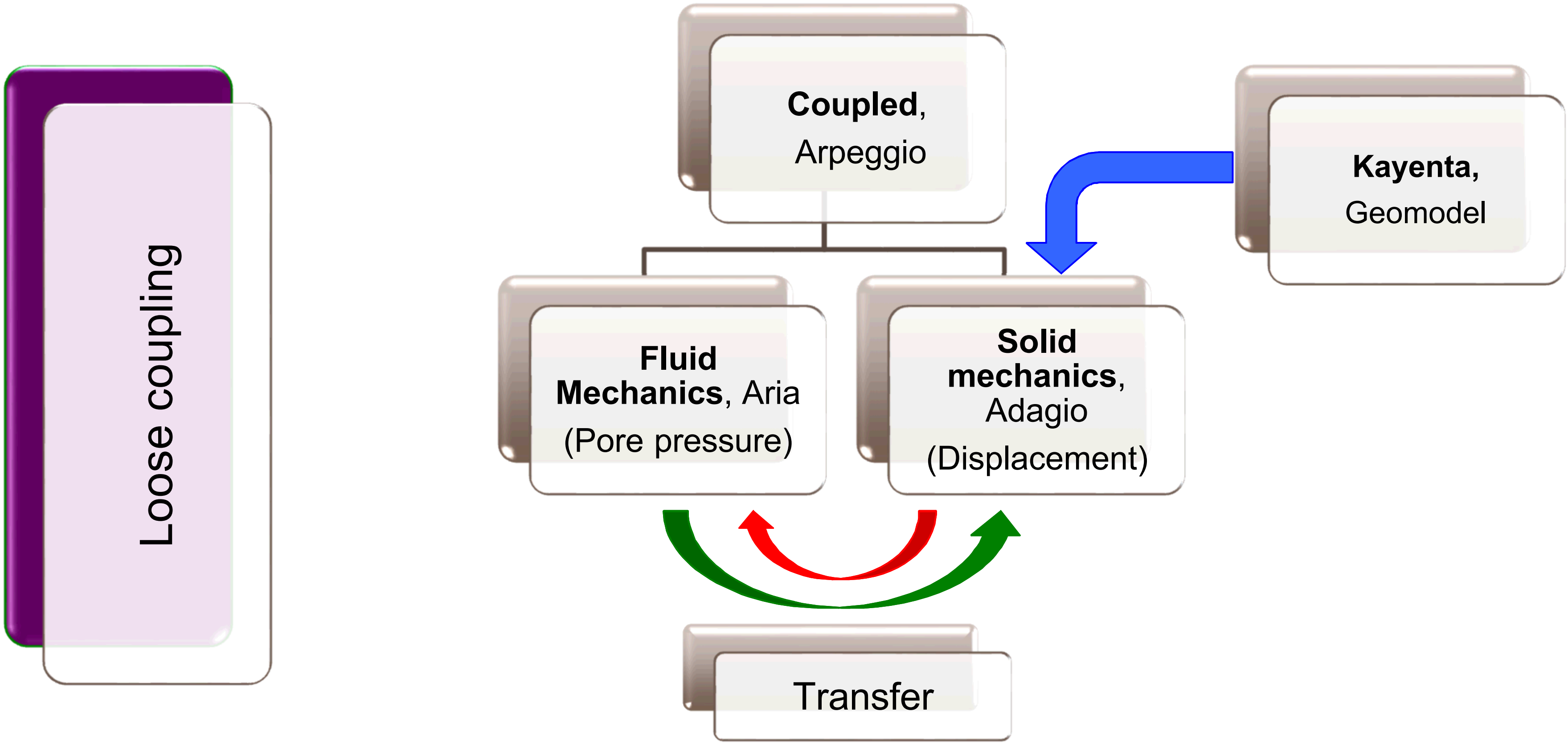
$$b = \frac{V_m}{1 - \frac{\sigma_n}{k_{ni}V_m}} - \frac{V_m}{1 - \frac{\sigma_{ni}}{k_{ni}V_m}}$$



Schematic of the jointed caprock

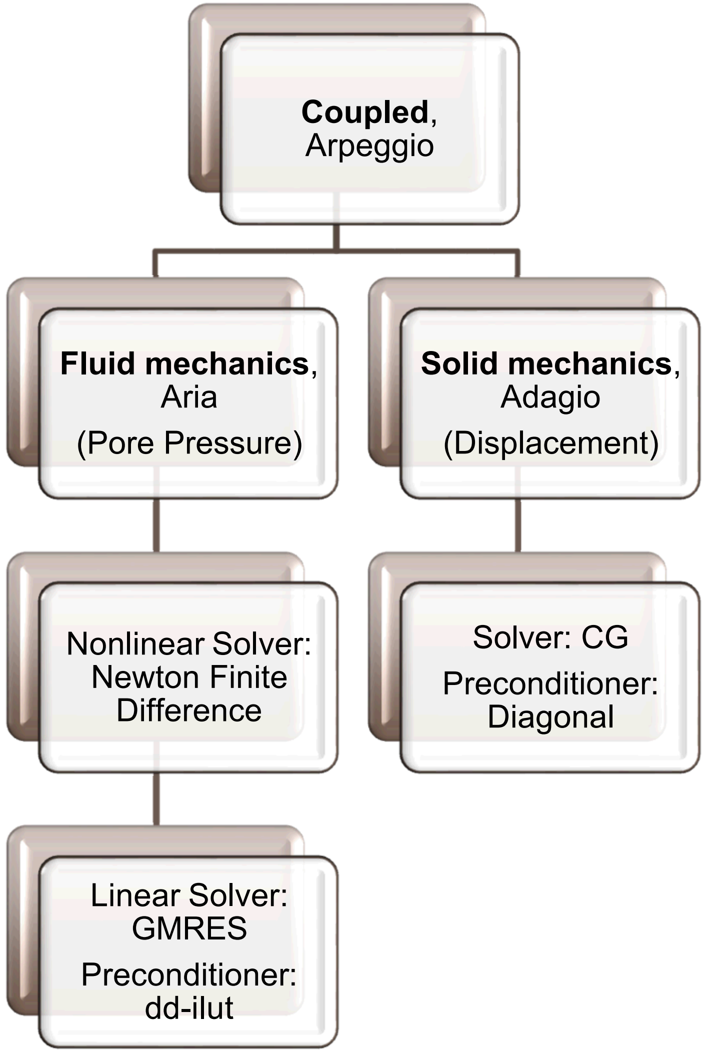


Sierra Mechanics



Aria: Galerkin FE program for coupled-physics problems described by systems of coupled PDEs
Adagio: 3-D, implicit, nonlinear Quasi-Statics; dynamics code
Arpeggio: Couples the Adagio, Aria, BEM, Calore and Premo Sierra Mechanics modules

Solver-Loose coupling



Properties

- Solid

Property	Aquifer	Caprock	Injection zone	Base	Units
Density	2100	2100	2100	2100	Kg/m^3
Biot's coefficient	1	1	1	1	
Young modulus	20	50	20	50	GPa
Poisson's ratio	0.2	0.12	0.2	0.12	

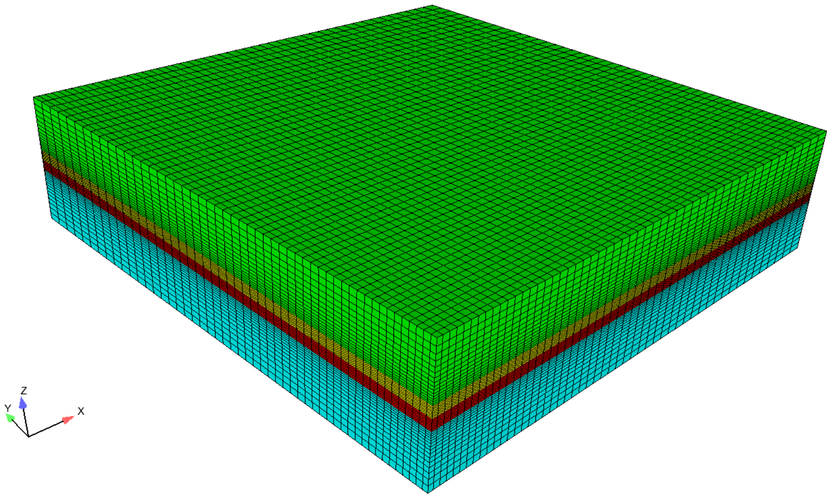
- Fluid

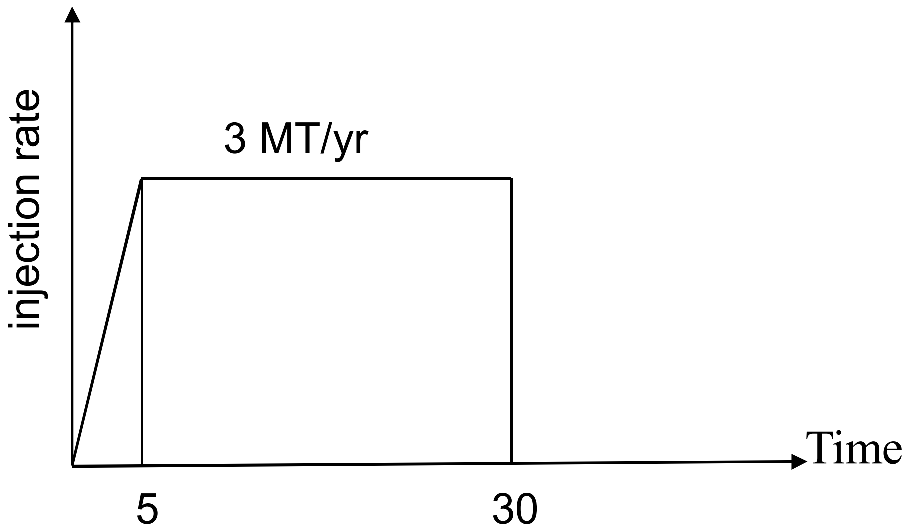
Property	Aquifer	Caprock	Injection zone	Base	Units
Initial porosity	0.15	0.05	0.15	0.10	
Intrinsic permeability	$2x10^{-14}$	$1x10^{-18}$	$2x10^{-14}$	$1x10^{-16}$	m^2

- Joint

Joint		
K_{ni} (Pa)	V_{max} (m)	S (m)
$1.5x10^{+10}$	$7.5x10^{-5}$	1.00

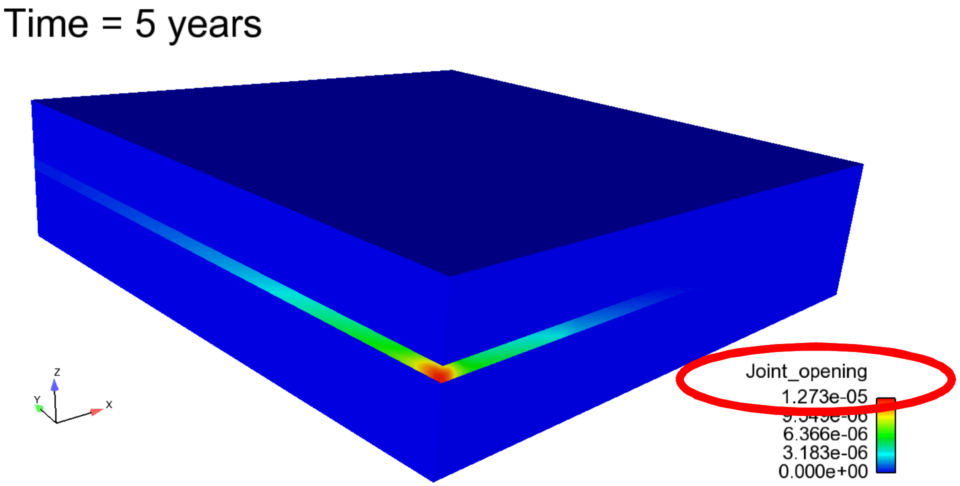
Model info



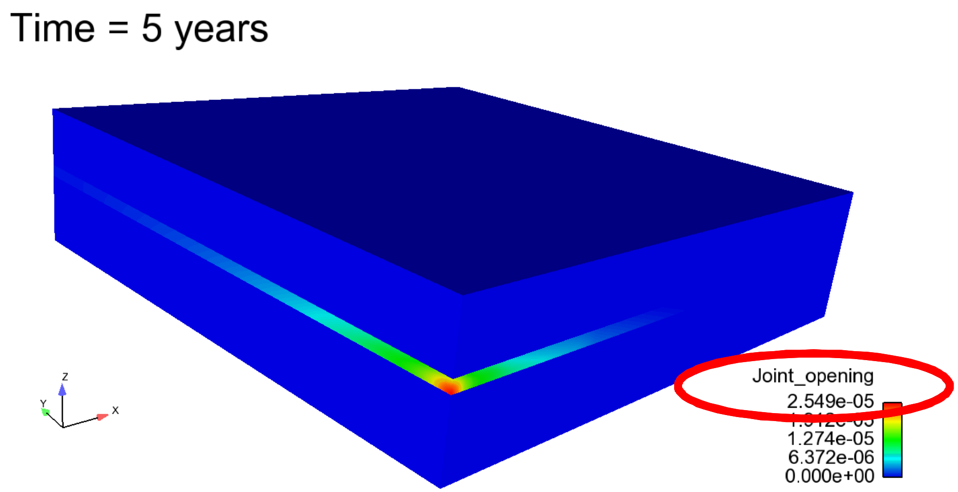


Mesh	Number of elements	Number of unknowns
1	120 K	600 K

Results

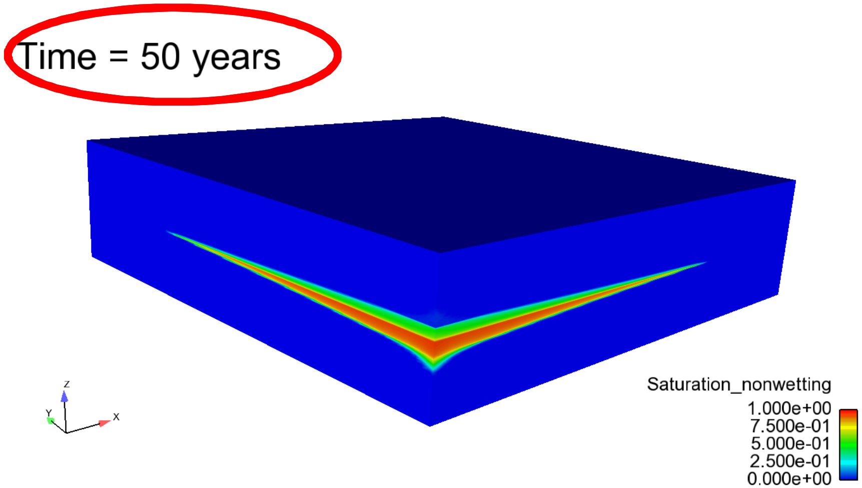


The joint opening through caprock layer for case with joint-3 Mt/yr, at 5 years of injection.

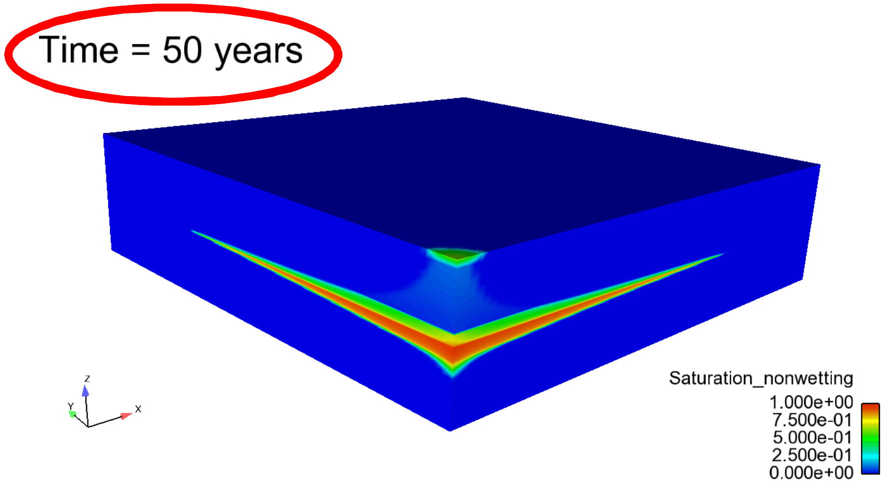


The joint opening through caprock layer for case with joint-5 Mt/yr, at 5 years of injection.

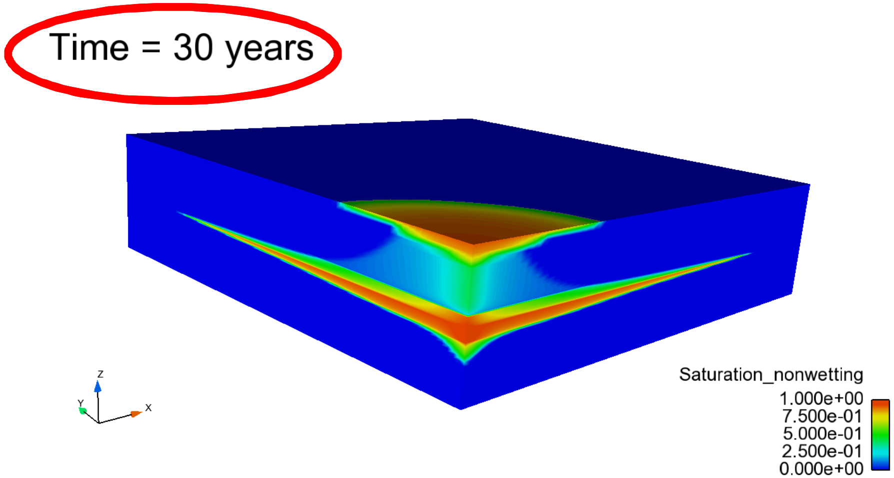
Results



The saturation of nonwetting phase for case without joint- 3Mt/yr, after 50 years of injection.

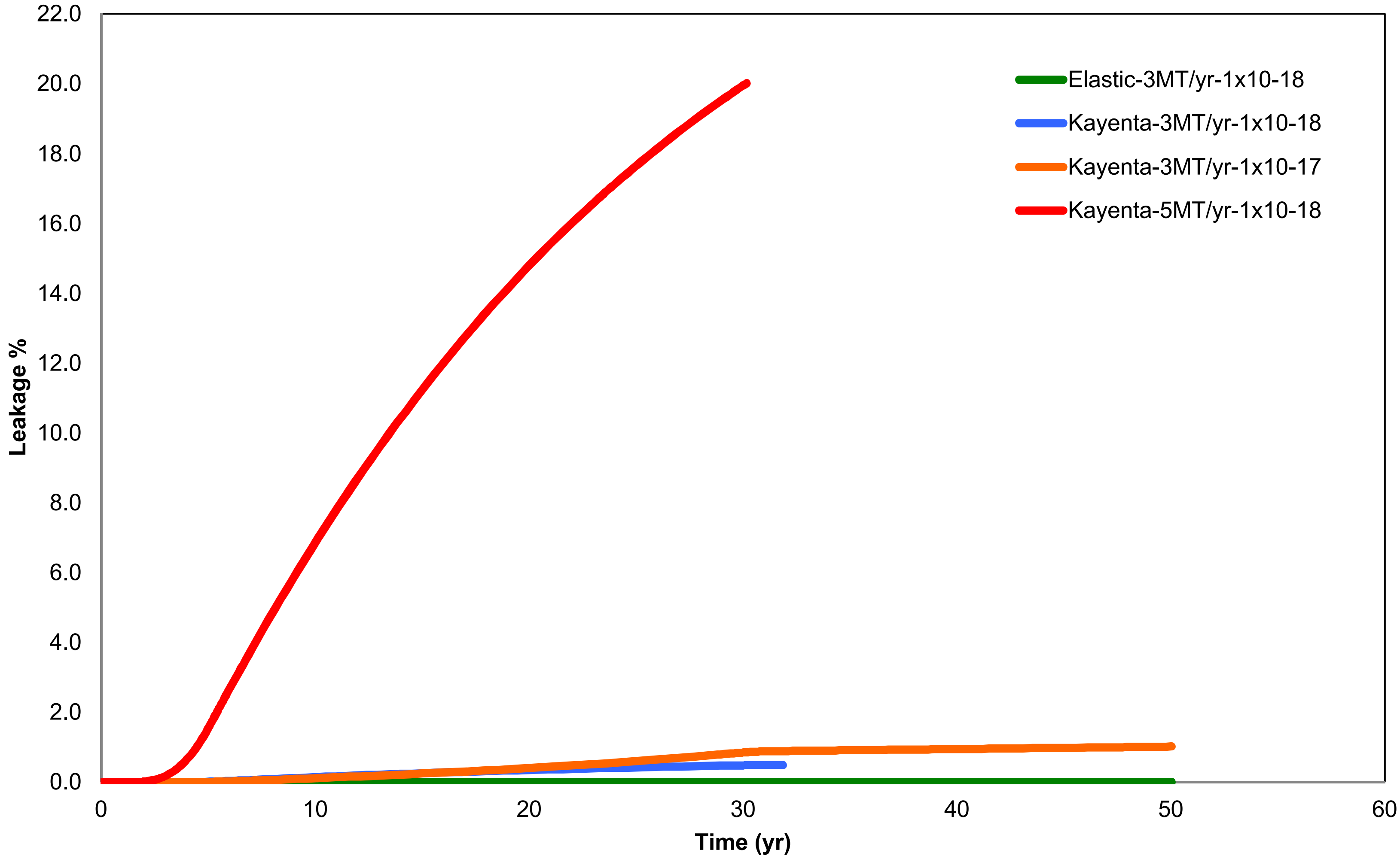


The saturation of nonwetting phase for case with joint-3 Mt/yr, after 50 years of injection.



The saturation of nonwetting phase for case with joint-5 Mt/yr, after 30 years of injection.

Results



Elastic-3MT/yr-1x10-18
Kayenta-3MT/yr-1x10-18
Kayenta-3MT/yr-1x10-17
Kayenta-5MT/yr-1x10-18
Leakage %
Time (yr)
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
10
20
30
40
50
60

Conclusions

- It is critical to include preexisting joints/fractures in caprock integrity analysis.
- Joint opening increases by increasing the injection rate.
- The change in the joint opening in the direction parallel to the joint set is more significant than the direction perpendicular to the joint set.
- Effective permeability within the caprock increases by increasing the injection rate.
- Percentage of the leakage to the total injection increases by increasing the injection rate.