CO_2 injection with fracturing in geomechanically protected caprock

Task 6 of LLNL's Research Activities to Support DOE's Carbon Storage Program (FWP-FEW0191)

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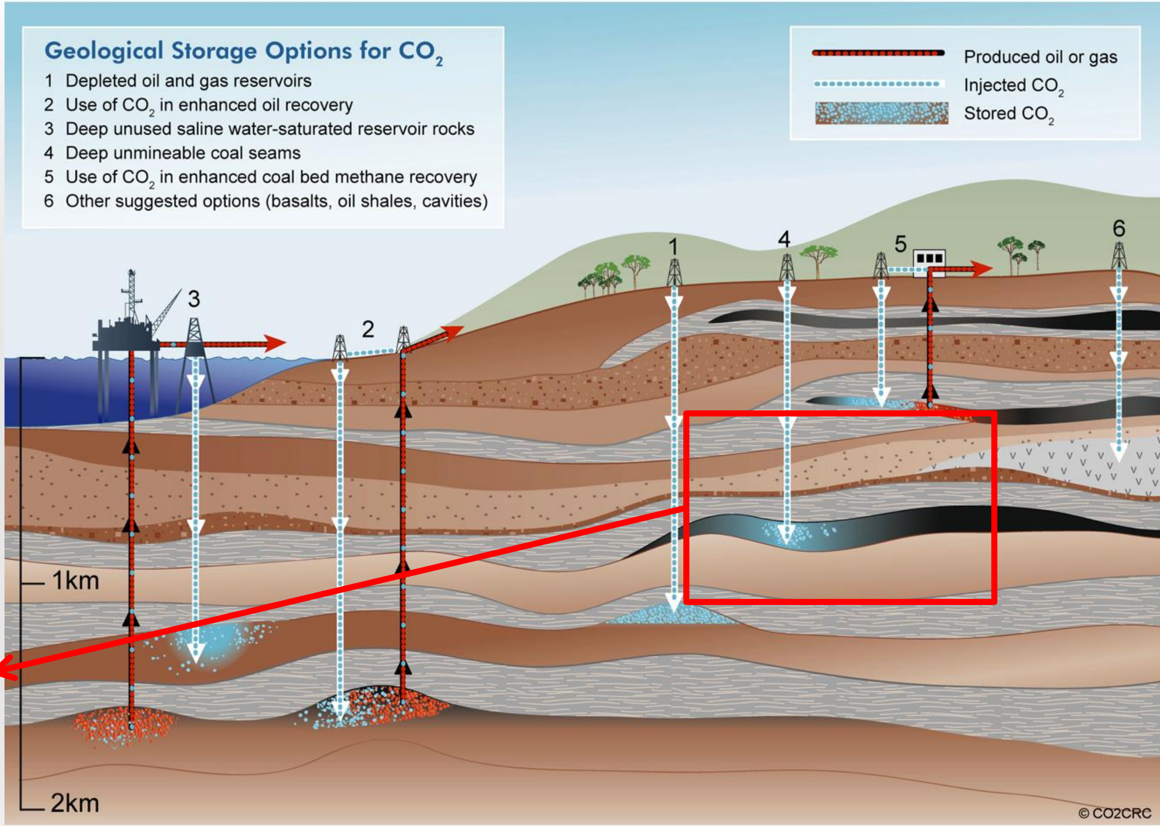
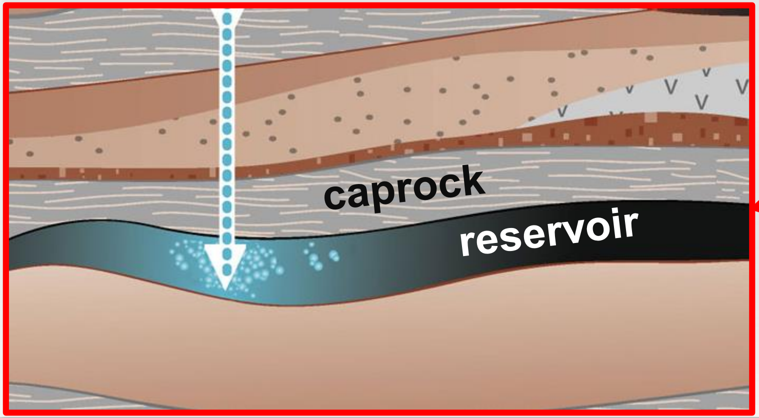
Background: geologic carbon storage (GCS)

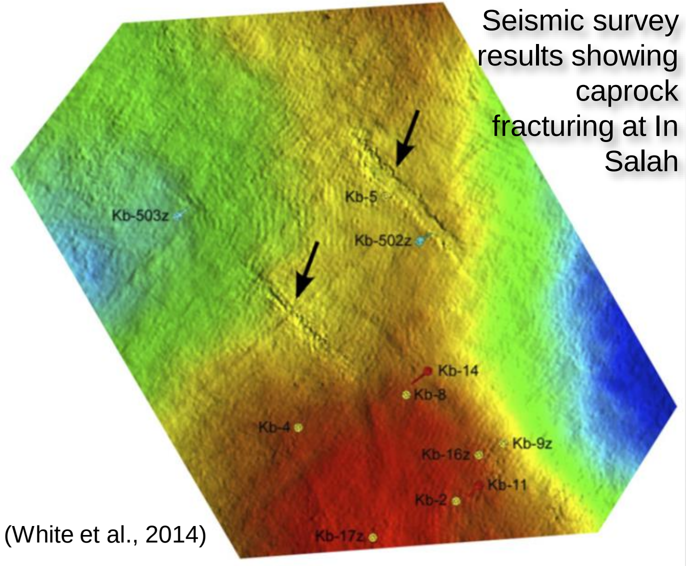
- 70% energy in US is from fossil fuel.
- Demands immense storage volume
- Local accessibility is a key
- Caprock secures integrity





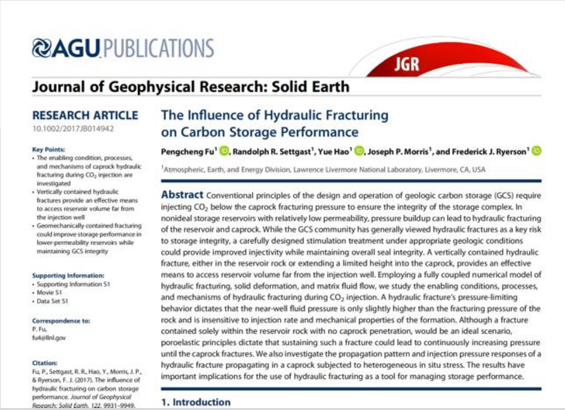
Why studying caprock fracturing

- Conventional strategy: Injecting below the fracturing pressure to prevent fracturing
- Hydraulic fracturing has been suspected.
  - Evidence showed the storage complex was not comprised.
- Need to re-assess the role of hydraulic fracturing in GCS.
- If CO_2 can be injected through a vertically contained fracture, reservoirs of marginal permeability will be economically viable.



Seismic survey results showing caprock fracturing at In Salah

(White et al., 2014)



AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

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Key Points:
- The enabling condition, processes, and mechanisms of caprock hydraulic fracturing during CO_2 injection are investigated
- Vertically contained hydraulic fractures provide an effective means to access reservoir volume far from the injection well
- Geomechanically contained fracturing could improve storage performance in lower-permeability reservoirs while maintaining GCS integrity

Supporting Information:
- Supporting Information S1
- Movie S1
- Data Set S1

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The Influence of Hydraulic Fracturing on Carbon Storage Performance

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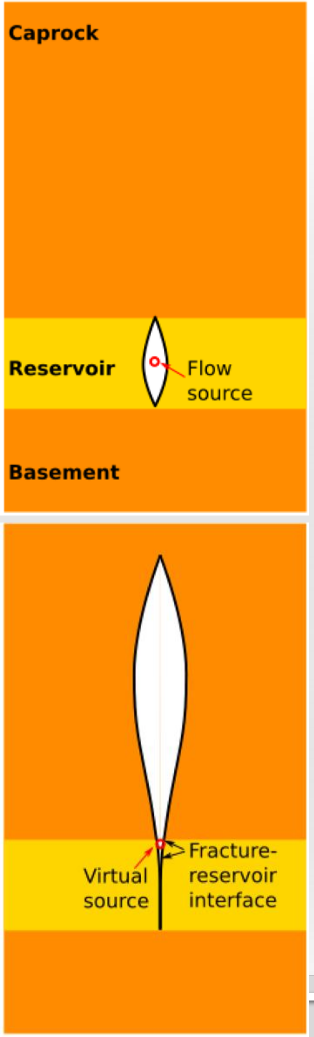
Abstract Conventional principles of the design and operation of geologic carbon storage (GCS) require injecting CO_2 below the caprock fracturing pressure to ensure the integrity of the storage complex. In nonideal storage reservoirs with relatively low permeability, pressure buildup can lead to hydraulic fracturing of the reservoir and caprock. While the GCS community has generally viewed hydraulic fractures as a key risk to storage integrity, a carefully designed stimulation treatment under appropriate geologic conditions could provide improved injectivity while maintaining overall seal integrity. A vertically contained hydraulic fracture, either in the reservoir rock or extending a limited height into the caprock, provides an effective means to access reservoir volume far from the injection well. Employing a fully coupled numerical model of hydraulic fracturing, solid deformation, and matrix fluid flow, we study the enabling conditions, processes, and mechanisms of hydraulic fracturing during CO_2 injection. A hydraulic fracture's pressure-limiting behavior dictates that the near-well fluid pressure is only slightly higher than the fracturing pressure of the rock and is insensitive to injection rate and mechanical properties of the formation. Although a fracture contained solely within the reservoir rock with no caprock penetration, would be an ideal scenario, poroelastic principles dictate that sustaining such a fracture could lead to continuously increasing pressure until the caprock fractures. We also investigate the propagation pattern and injection pressure responses of a hydraulic fracture propagating in a caprock subjected to heterogeneous in situ stress. The results have important implications for the use of hydraulic fracturing as a tool for managing storage performance.

1. Introduction

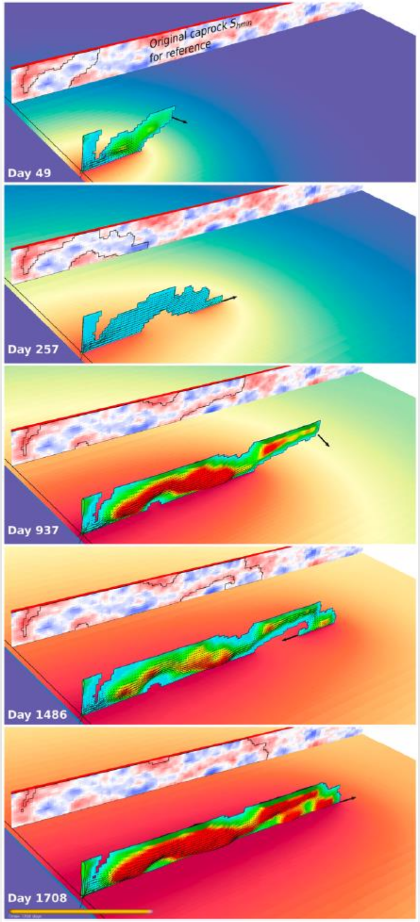
Project Overview

- To assess short- and long-term behavior of hydraulic fractures in geomechanically protected caprock.
  - Goal is to increase injectivity in low-permeability reservoirs and ensure storage security.
  - Develop mechanically rigorous tools to evaluate various fracturing scenarios.
  - In essence, we bring rigorous fracture mechanics, geomechanics, and multi-phase flow together to evaluate caprock fracturing.
- Funded by DOE/NETL.
- Performance dates: July 1, 2018 to September 30, 2020



Tasks and technical approach

- Tasks:
  - Develop and validate a CO_2-saline two-phase hydraulic fracture model in GEOS.
  - Study the sustainability of hydraulic fracture within the reservoir rock.
  - Study fracturing mechanisms and processes unique to CO_2 injection.
  - Study fracture containment mechanisms.
- Technical approach:
  - High fidelity modeling utilizing HPC.



Is hydraulic fracture in reservoir rock poromechanically sustainable?

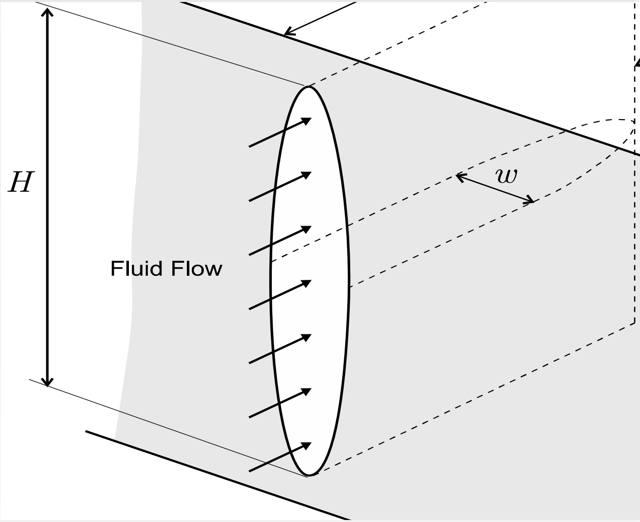
- A hydraulic fracture tends to close under constant fluid pressure
  - (Detournay and Cheng, 1991; …)
- Can we sustain a reservoir hydraulic fracture with a pressure safe for caprock?

Unconventional oil and gas:

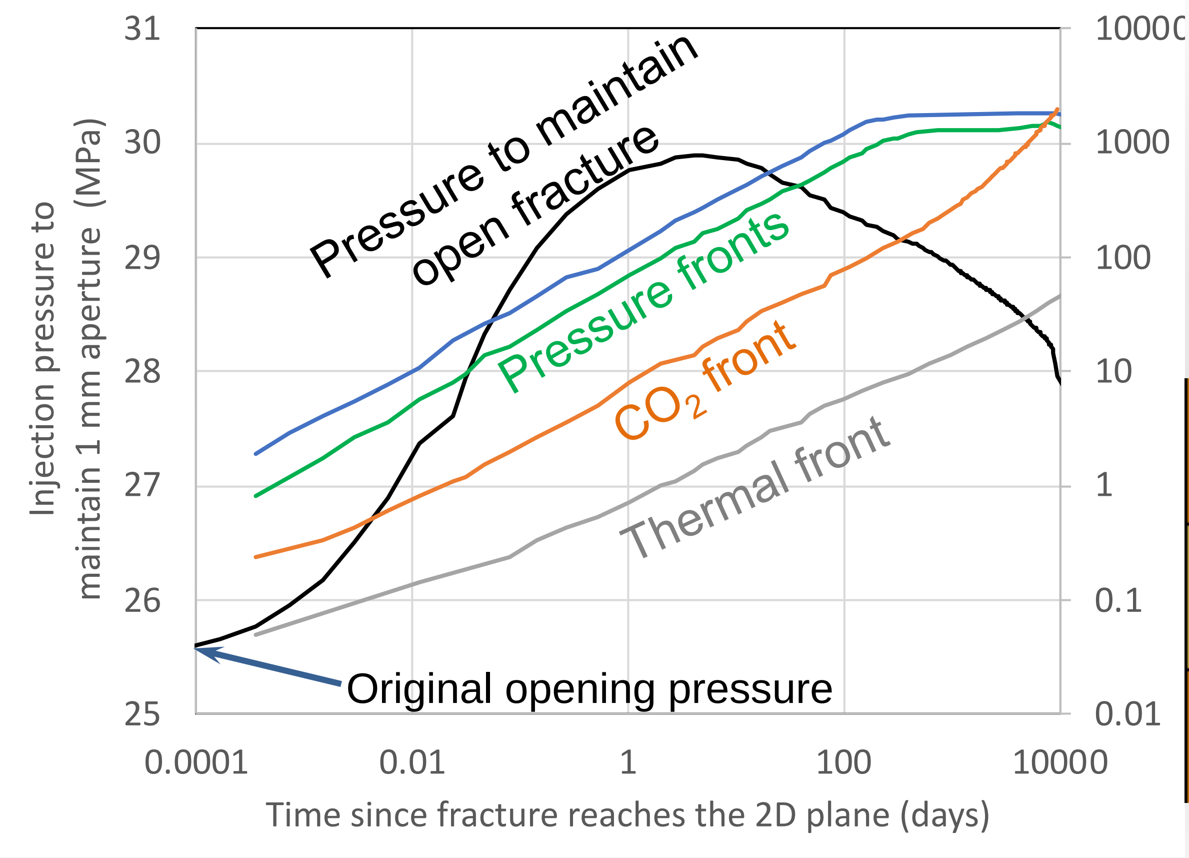
- Very low reservoir *k*
- Can use high viscosity fluid
- Relatively short injection

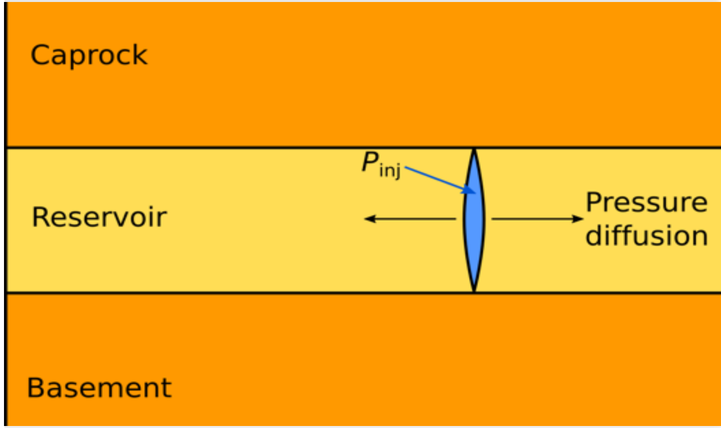
Carbon storage:

- Much higher reservoir *k*
- Has to inject CO_2
- Long injection



Fracture's poroelastic sustainability: baseline results





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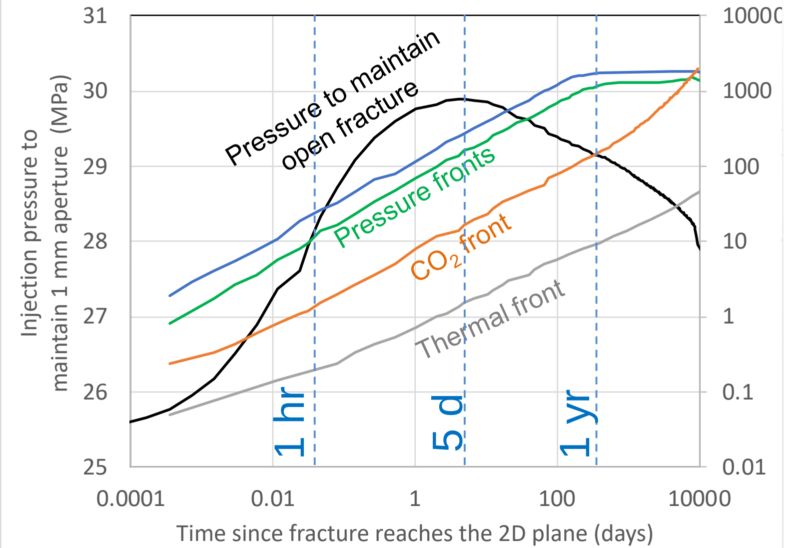
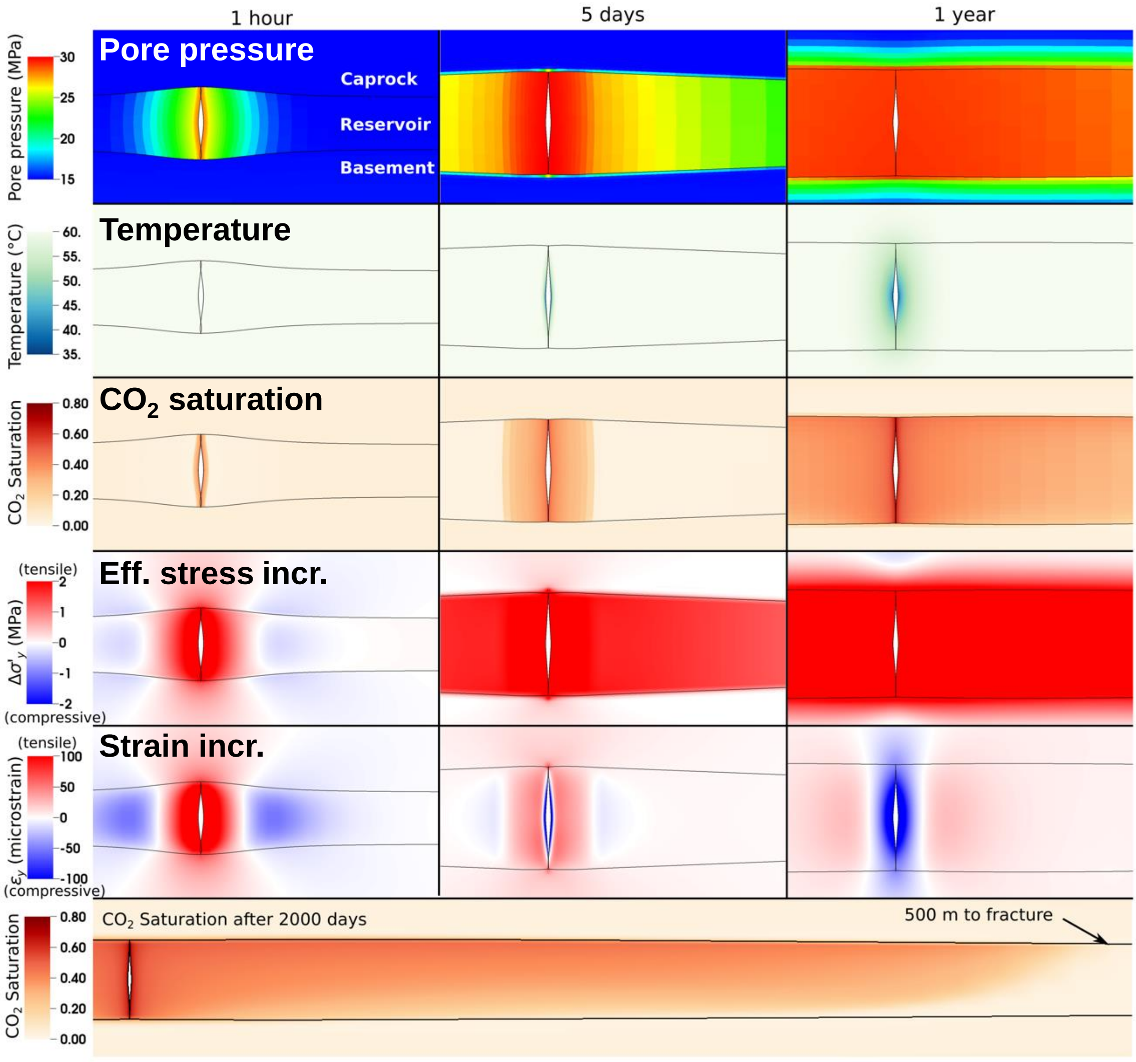




Poroelastic effect causes expansion of reservoir (closing fracture).

Fracture opened by fracture loading + Poisson's effect + thermal contraction.

Reservoir total stress increase due to poromechanical effects

$$\bar{P}_\mathrm{f}^\mathrm{o} = P_\mathrm{Int} + \frac{1-\nu}{1-\nu-b+2b\nu}\left(S_\mathrm{hmin} - P_\mathrm{Int}\right)$$

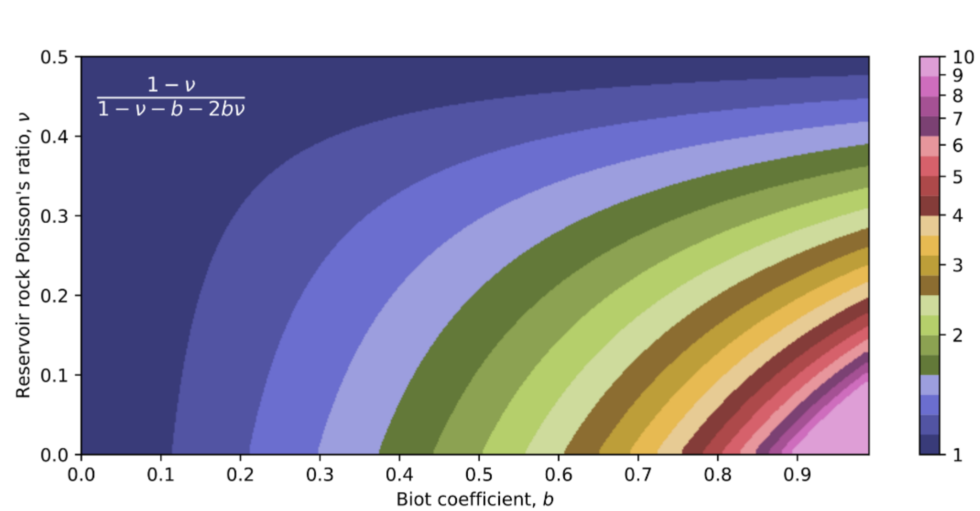
$\bar{P}_\mathrm{f}^\mathrm{o}$: Ultimate fracture-opening pressure

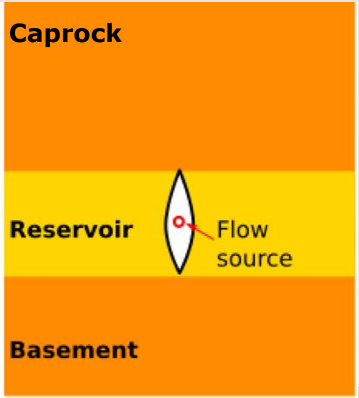
P_Int: Initial reservoir pore pressure

S_hmin: Initial in situ stress, reservoir

ν: Poisson's ratio

b: Biot's coefficient





S_hmin=28 MPa

S_hmin=25 MPa, P_Int=15 MPa, ν = 0.25, b = 0.5

$\bar{P}_\mathrm{f}^\mathrm{o}$ = 30 MPa

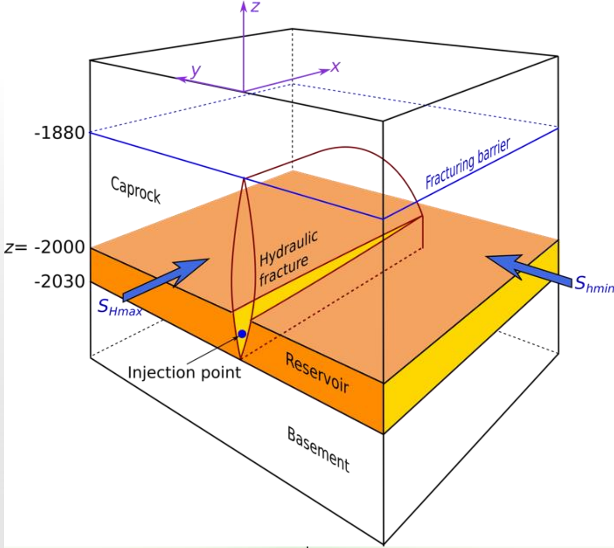
Needs a 3D high-fidelity model to study complex scenarios

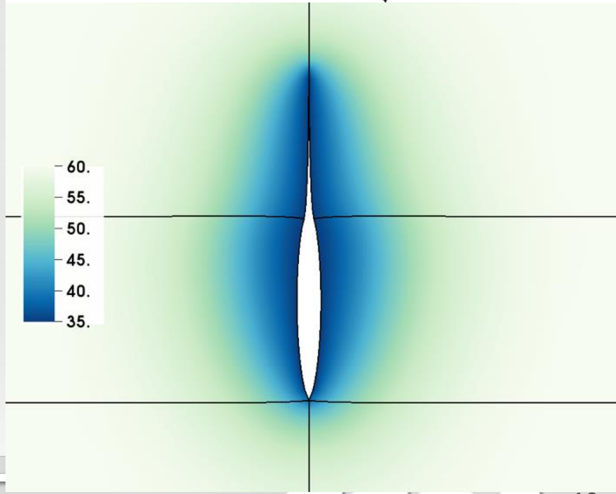
Framework of the 3D model:

- Critical processes as revealed by 2D model
  - Fluid/heat transport
  - Poroelasticity
  - Poisson’s effect
  - Thermal contraction
  - Fracturing through stress barrier

- Take advantage of existing GEOS modules:
  - CO_2-saline flow module
  - Hydraulic fracturing module

- A key revelation allowing mitigating numerical challenges:
  - In leakoff-dominated fracturing regime, only minimal error is induced if mass conservation fracture is relaxed.

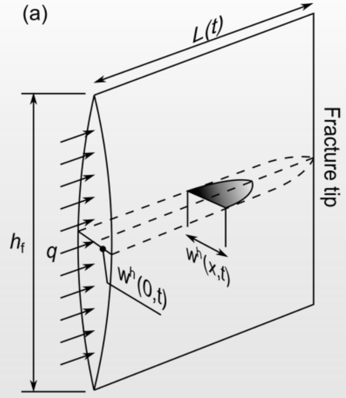


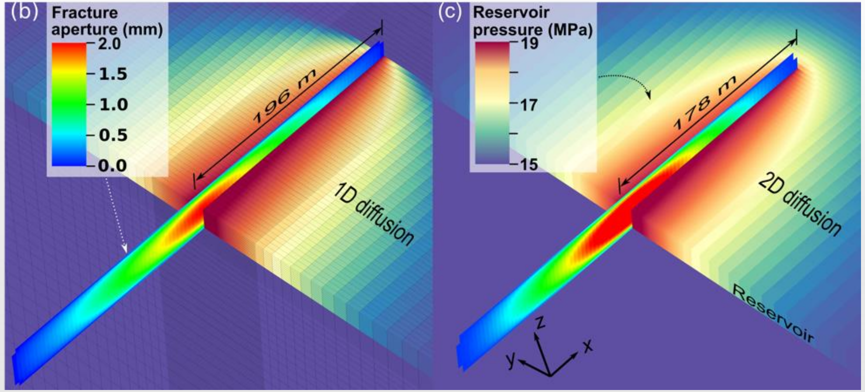


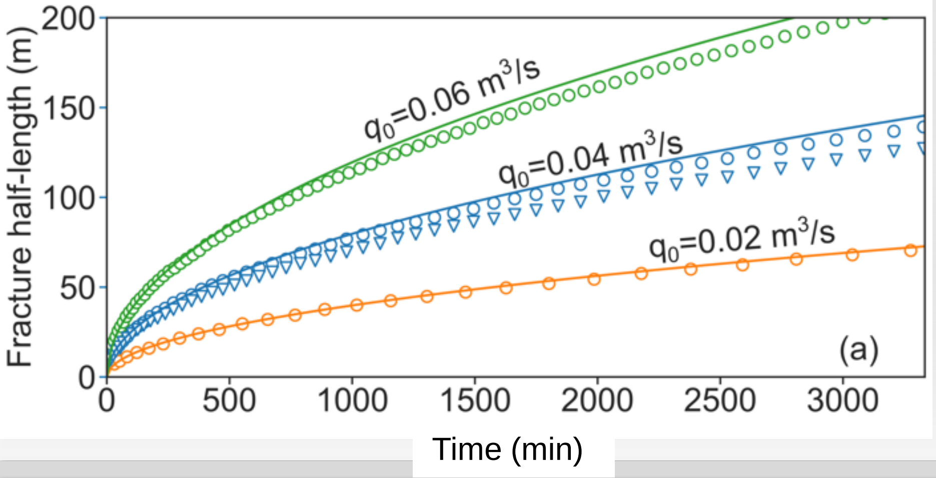
Model verification: leakoff-dominated fracture propagation

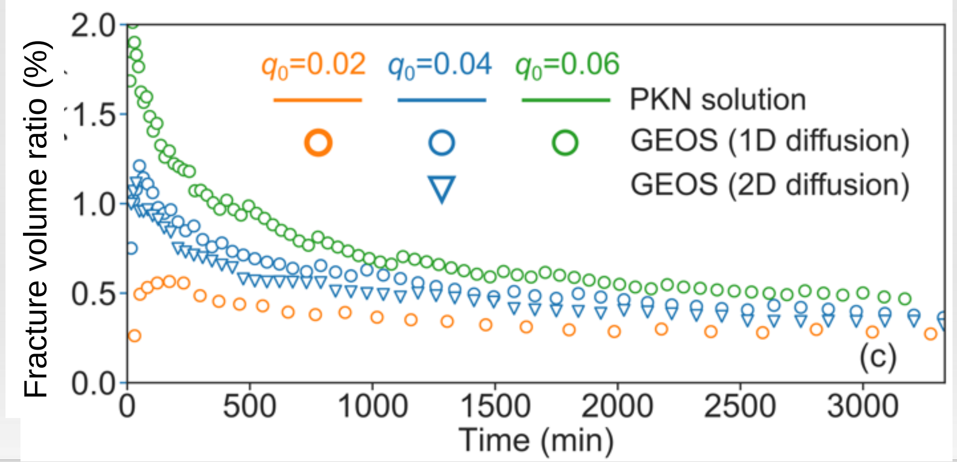
$$L = \frac{q t^{1/2}}{2\pi C_{\mathrm{L}} h_{\mathrm{f}}}$$

$$w_0^{\mathrm{h}} = 4\left[\frac{\mu q^2}{\pi^3 E' C_{\mathrm{L}} \mathrm{h}_{\mathrm{f}}}\right]^{\frac{1}{4}} t^{1/8}$$

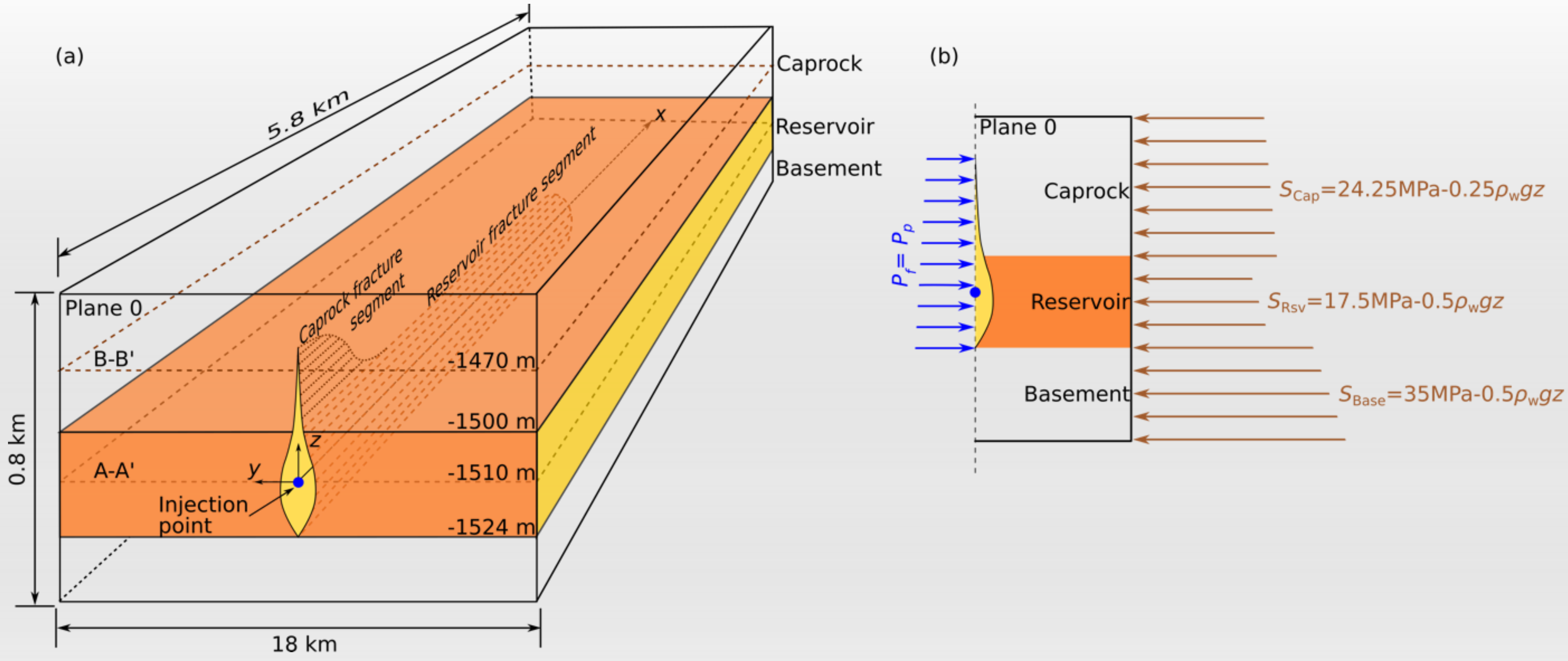








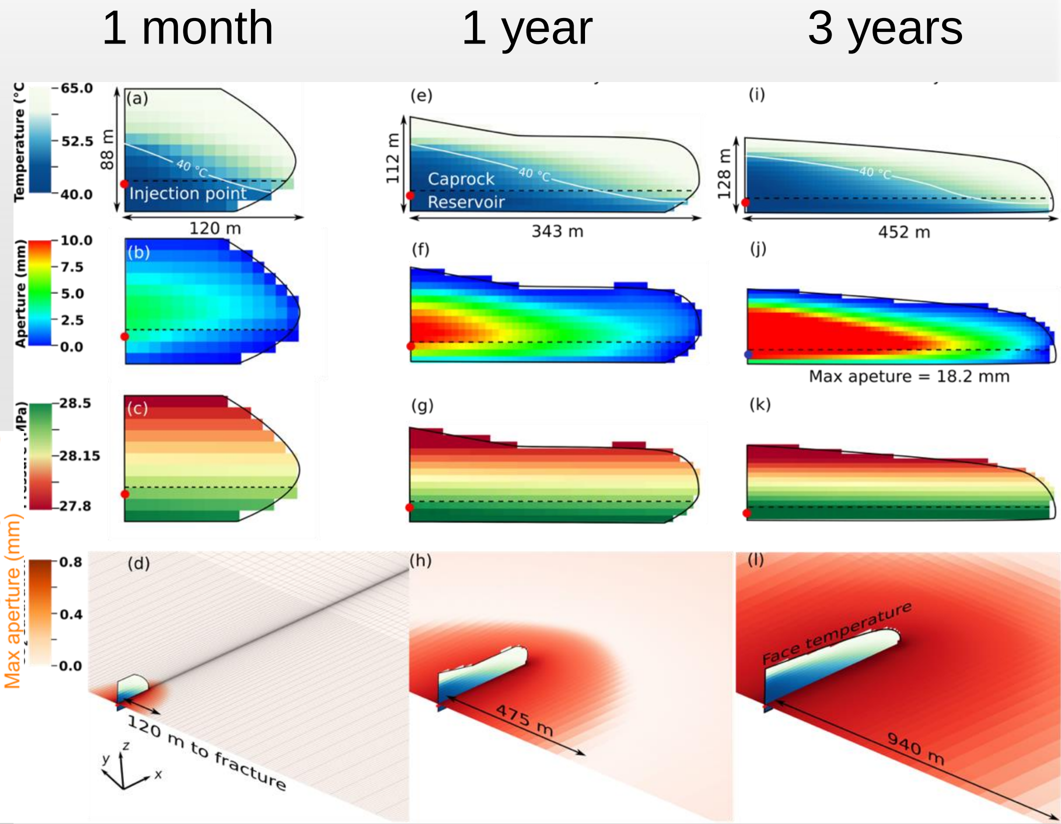
Model setup

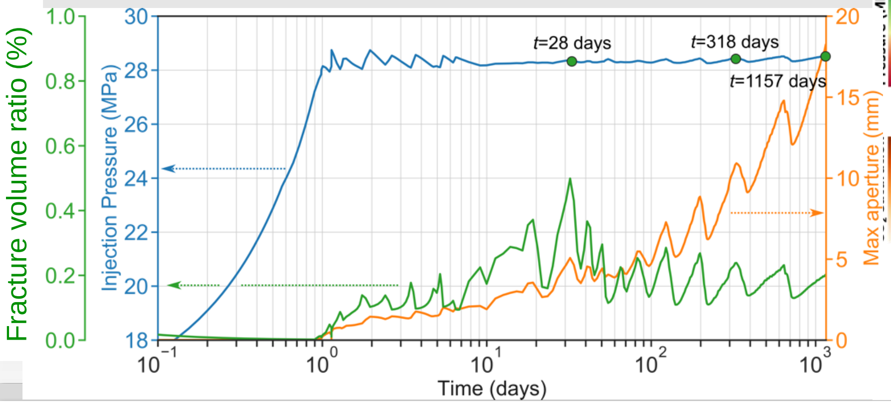


(a)
5.8 km
Caprock
Reservoir
Basement
x
Reservoir fracture segment
Caprock fracture segment
Plane 0
B-B'
-1470 m
-1500 m
z
A-A'
y
-1510 m
Injection point
-1524 m
0.8 km
18 km
(b)
Plane 0
Caprock
$P_f = P_p$
Reservoir
Basement
S_{Cap}=24.25MPa-0.25$\rho_w gz$
S_{Rsv}=17.5MPa-0.5$\rho_w gz$
S_{Base}=35MPa-0.5$\rho_w gz$

Model results: key processes

- Rapid increase of injection pressure due to poroelasticity (total stress increase)
- Early: caprock fractures leads
- Later: caprock fracture follows
- Extra large aperture due to thermal
- Thermal contraction impedes height growth





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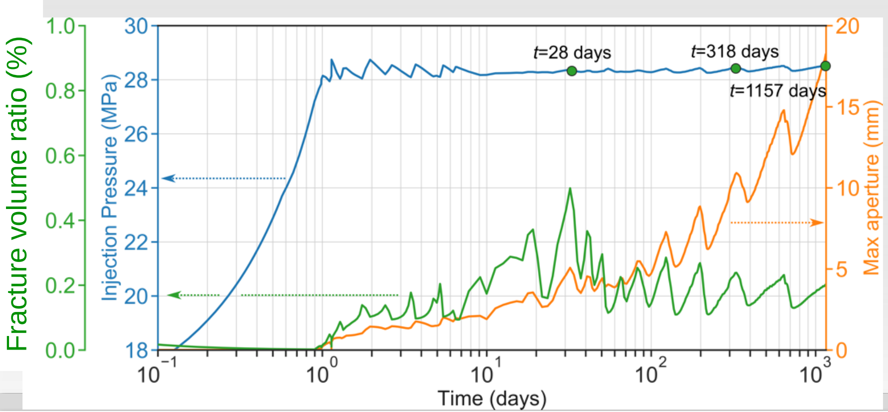
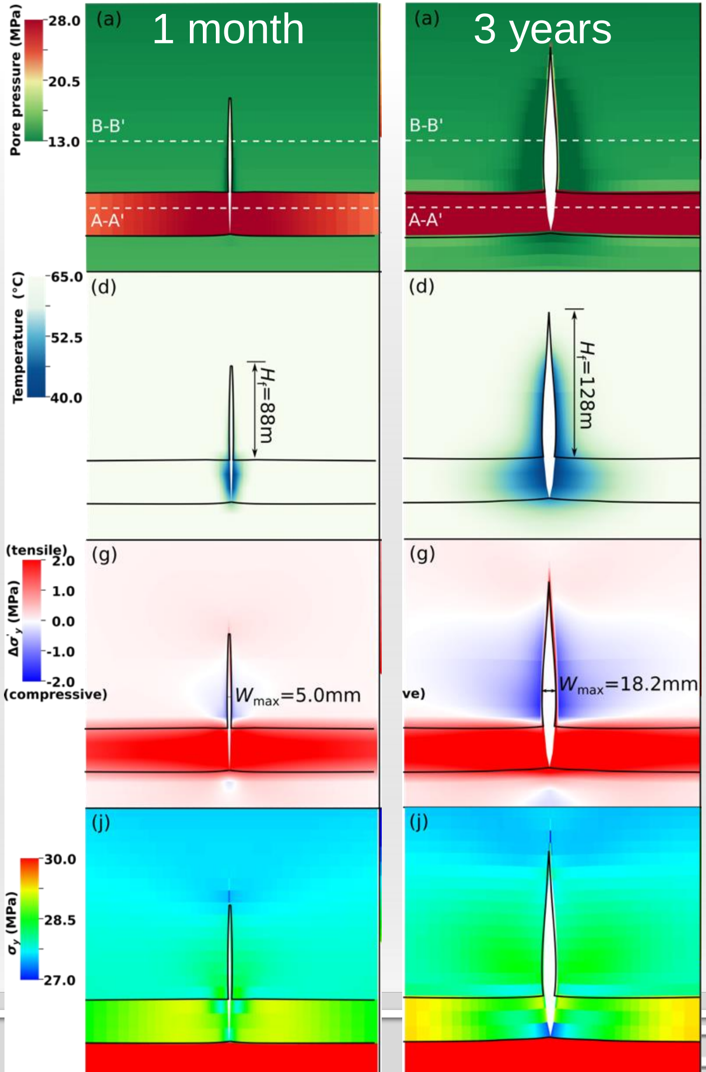
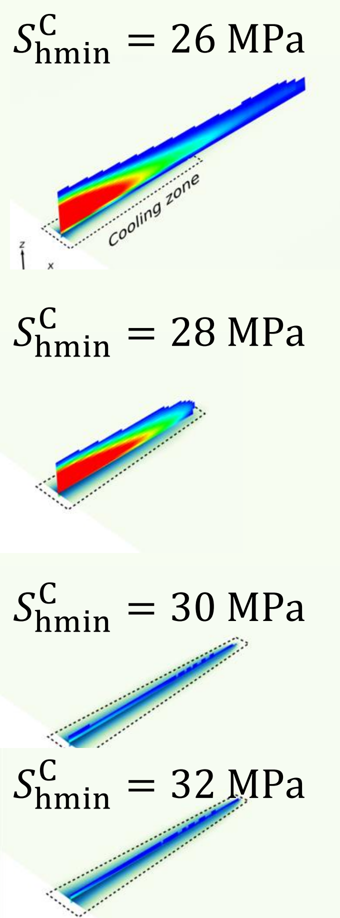
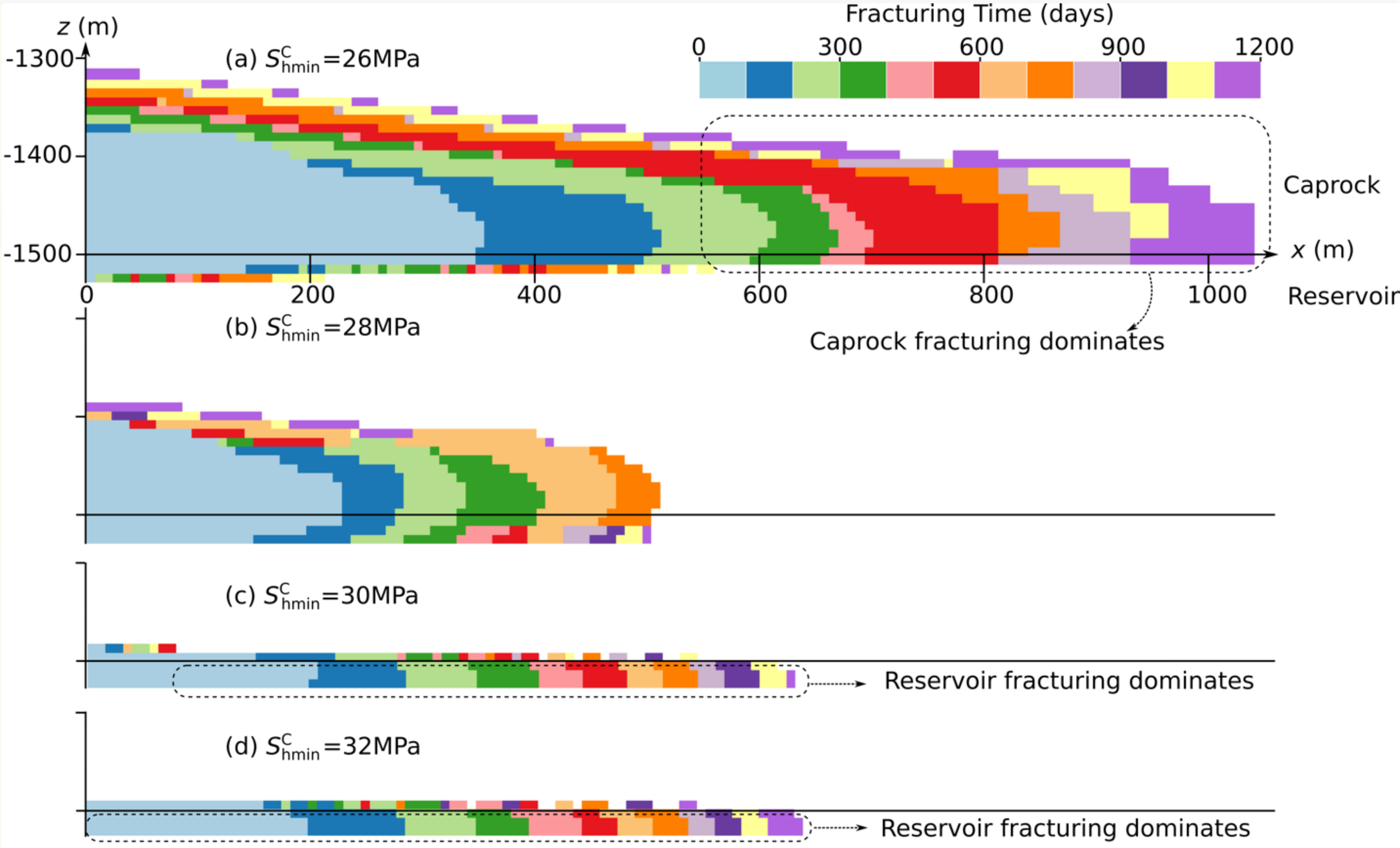




Model results: the effects of caprock in situ stress

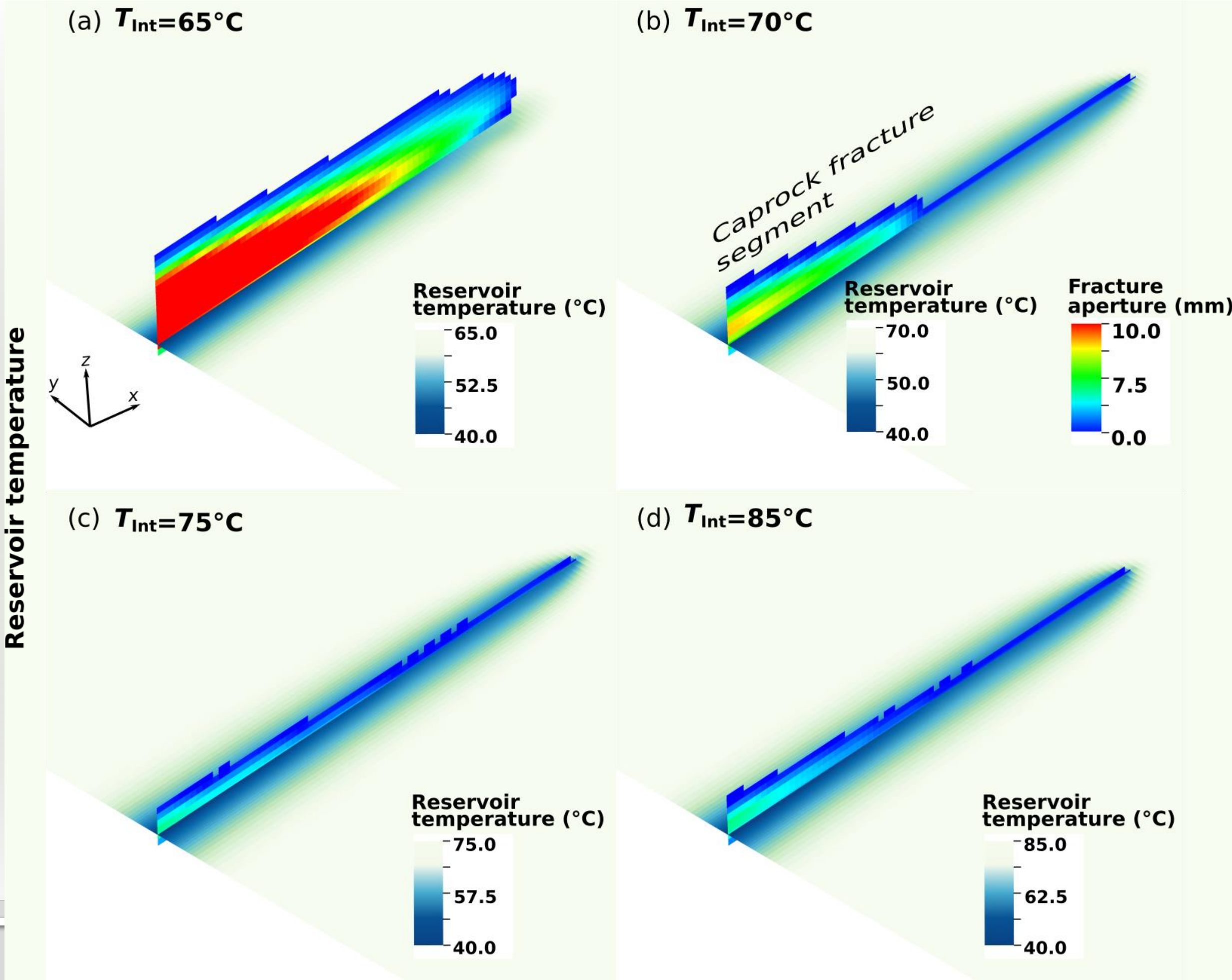
- High caprock stress limits fracture height growth





Model results: the effects of caprock temperature

- High caprock temperature limits fracture height growth

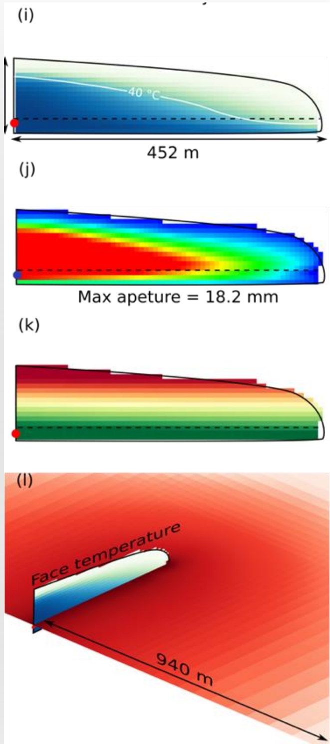


Technical status and impact

- Success completion of this two-year effort.
  - Paper on poroelastici sustainability in minor revision.
  - Paper on 3D model and containment mechanism will be submitted before October.
  - Model available in GEOS.

- The results could motivate a fundamental shift in exploration/design focuses:
  - Fracture growth is affected by many previously unappreciated factors
  - Looking for systems with caprock protected by certain inherent geomechanical features.
  - Particularly when only marginal k reservoir is available.

Layering structure of typical sedimentary rocks



- Addresses several priority research directions
  - *PRD S-6 (fault and fracture systems), S-3 (control of near-well environment) , S-2 (dynamic pressure limit), S-1 (Multiphysics and multiscale fluid flow)*

Lesson learned and synergy opportunities

- Fracturing and fracture flow in GCS context is still poorly understood.
- When we incorporate more physics, new understanding emerges.
  - The process should make sense in hindsight, but would be hard to think of without the aid of high-fidelity models.
- Synergistic with
  - Ongoing studies of stress measurement, fault activation
  - Fracturing research in geothermal and oil-gas applications.
- Addresses several priority research directions
  - PRD S-6: Improving Characterization of Fault and Fracture Systems
  - PRD S-3: Optimizing Injection of CO2 by Control of the Near-Well Environment
  - PRD S-2: Understanding Dynamic Pressure Limits for Gigatonne-scale CO2 Injection
  - PRD S-1: Advancing Multiphysics and Multiscale Fluid Flow to Achieve Gigatonne/year Capacity

LLNL-PRES-123456

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