Managing a Gigatonne CCS Future: A Framework for Basin-Scale Storage Optimization Based on Geomechanical Studies

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Yves Guglielmi, Abdullah Cihan (LBNL)

Jens Birkholzer, Meng Cao, Stanislav Glubokovskikh, Matthew Reagan, Jonny Rutqvist, Preston Jordan, Frédéric Cappa, Hafssa Tounsi, Utkarsh Mital

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Overall Project Objectives

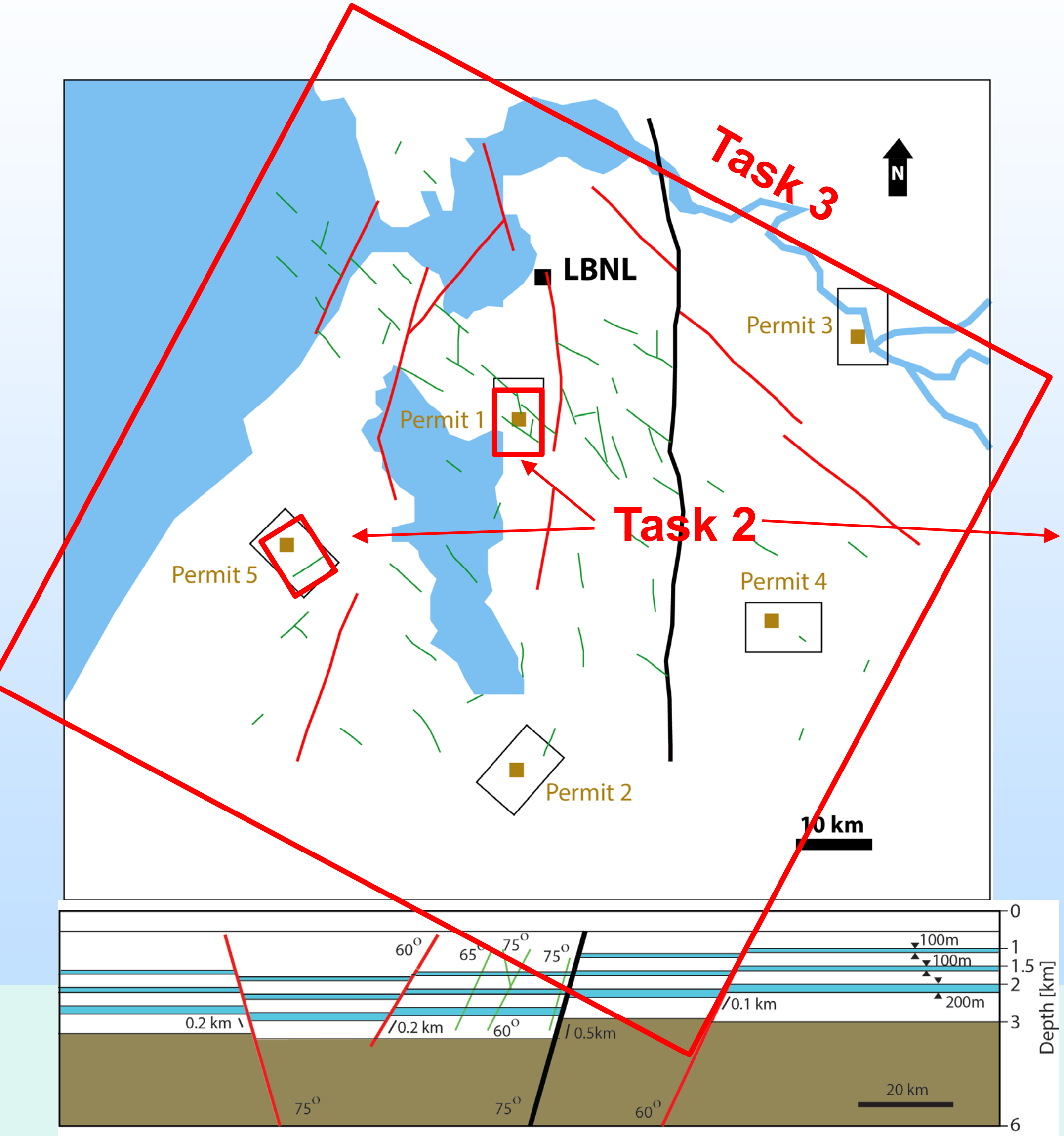
Develop a Framework for Simulation-Based Storage Management and Storage Optimization at the Basin Scale

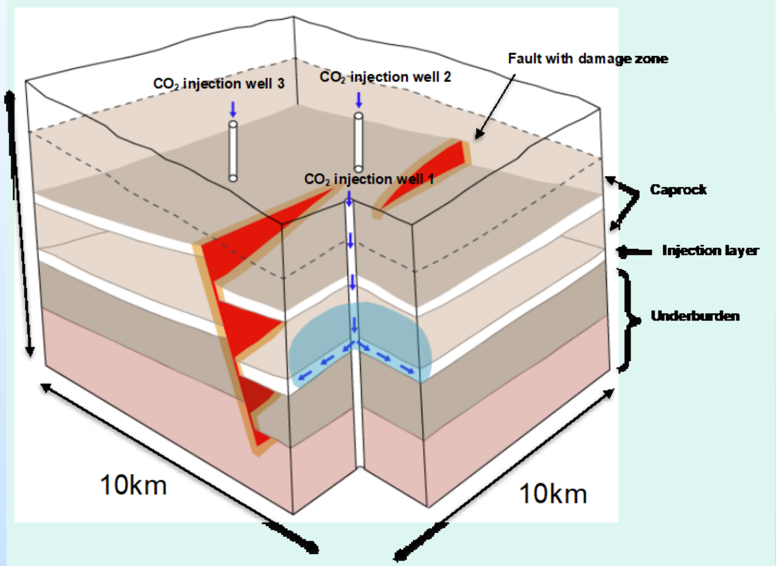
Task 2: Transfer fault geomechanics knowledge derived from small-scale in-situ research experiments and/or pilot/demonstration to larger injection volumes and scales so that we can simulate with confidence important geomechanical effects at the scale of large storage complexes.

Task 3: Via a basin-scale simulation and optimization framework, gain a sound understanding of the basin-scale impacts of a gigatonne CCS future, and develop a flexible workflow for simulation and optimization that can be handed over to institutions tasked with regional CO_2 storage hub planning.

Building a Synthetic Basin

To interact between Tasks 2 and 3

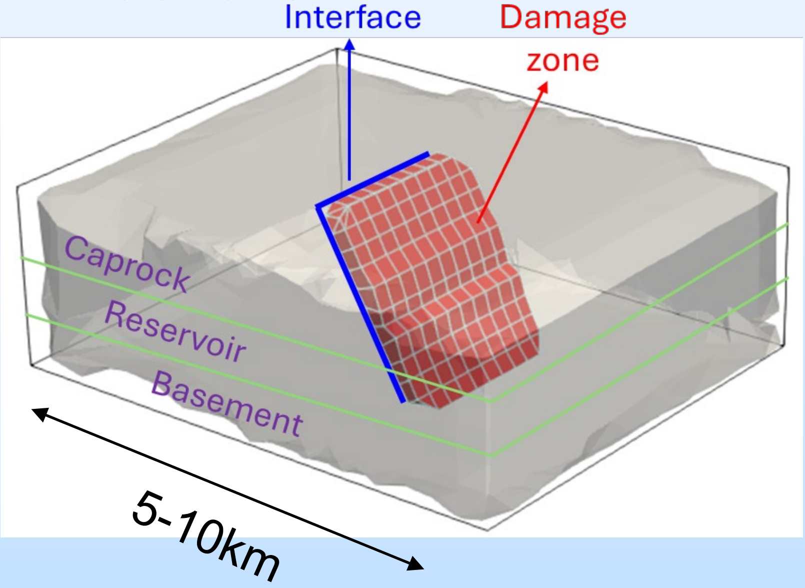




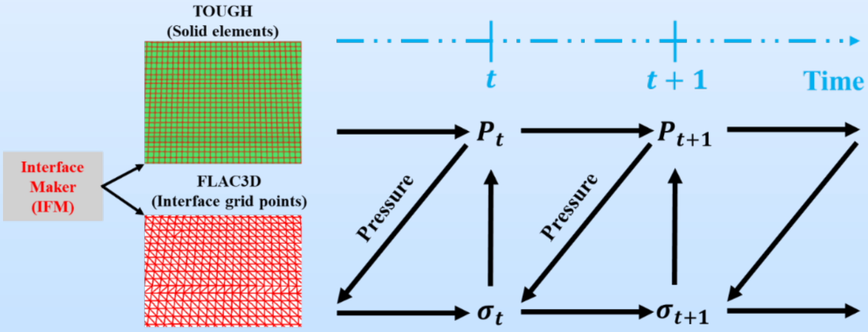
Including explicit faults in a large poroelastic layered volume

Task 2 - Advanced 3D fully coupled modeling at 5-10 km scale

- Three-dimensional
- Complex fault geometry (finite length, thickness, curvature)
- Refined 20m fault mesh elements



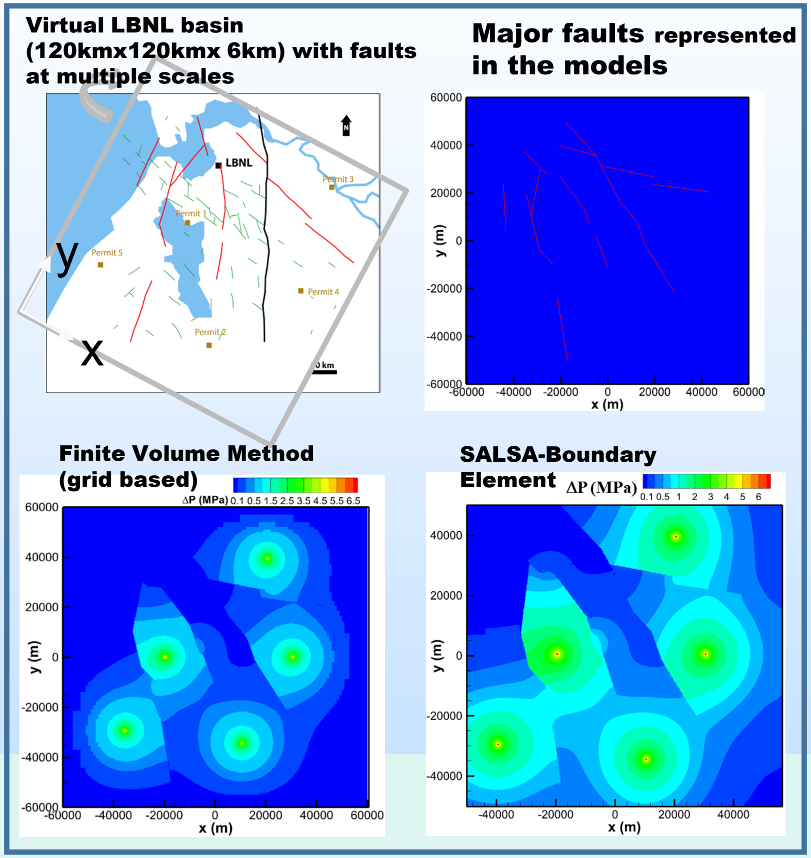
- Multiphase fluid flow modeling of supercritical CO_2 injection in brine
- Sequential hydro-mechanical coupling
- Elasto-plastic constitutive laws
- Finite difference – Finite volume methods



Calculating a 20 years long injection at 25kg/s

Task 3 - Simplified 3D fully coupled modeling at basin scale

- Grid-based numerical models
  - 3D fully coupled poroelastic models (Finite Volume Method-based)
    - Single-phase and two-phase fluid flow
    - Quasi-static and dynamic elasticity (wave propagation)
- Boundary Element - SALSA code
  - Laplace transform + Boundary Element approach to predict transient pressure and stress changes
  - Fault barriers and heterogeneities
- Tensor transformation algorithms built into the models
  - Rapid assessment of slip tendency and Coulomb failure stress (CFS) changes on faults
- Constrained differential evolution optimization algorithm
  - Well placement, injection/extraction control
  - Maximize CO_2 storage with constraints such as fault slip and fracturing pressure



Virtual LBNL basin (120kmx120kmx 6km) with faults at multiple scales

Major faults represented in the models

Finite Volume Method (grid based)

SALSA-Boundary Element

Physics transferred to basin scale

In red, the physics tested so far !

Coupled THM processes

- **Effect of multiphase CO2-brine flow**
- **Effect of fault geology (length, shape,…)**
- **Effects of Poro-elasticity and Effective stress variations on Mohr-Coulomb failure**
- **Effect of pressure diffusion on induced seismicity**
- More advanced fault rupture constitutive laws **related to rates**
  - Weakening *(and mechanical instability = seismicity)*
  - Permeability change
- Effect of CO_2 properties on fault rupture evolution

Reservoir Engineering

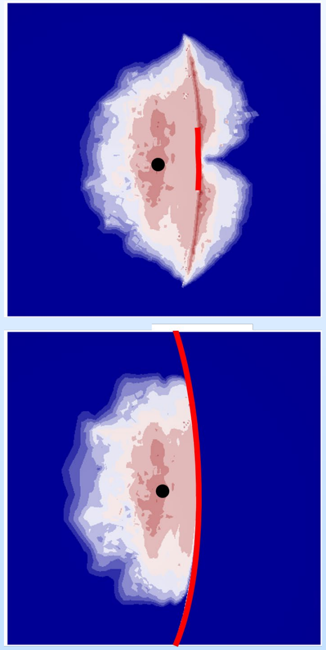
- **Well placement vs fault location**
- **Injection scenarios (injection rate variations)**

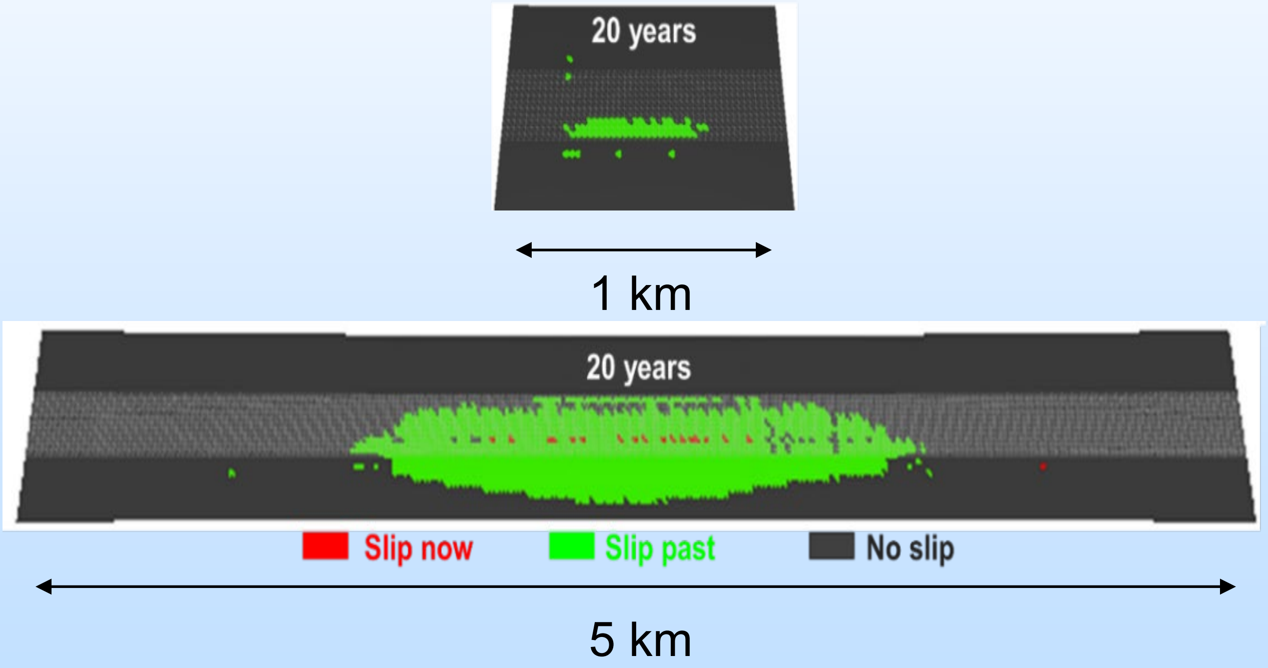
Effect of fault geology (length, shape,…)

Case of an impermeable fault

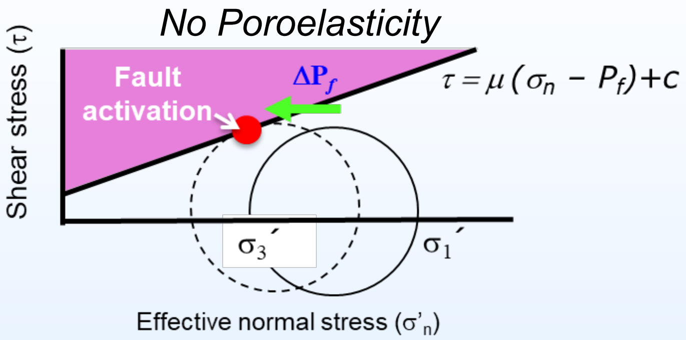
Less rupture on a small fault that can be by-passed !

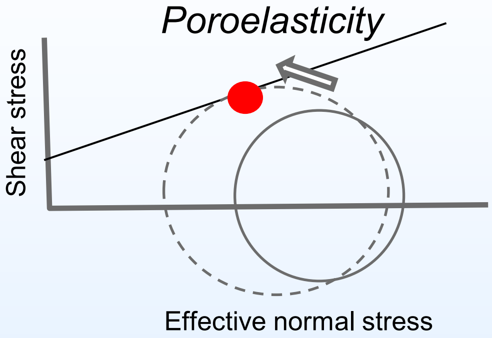
Storage reservoir
Pore pressure





Effects of Poro-elasticity and Effective stress variations on Mohr-Coulomb failure



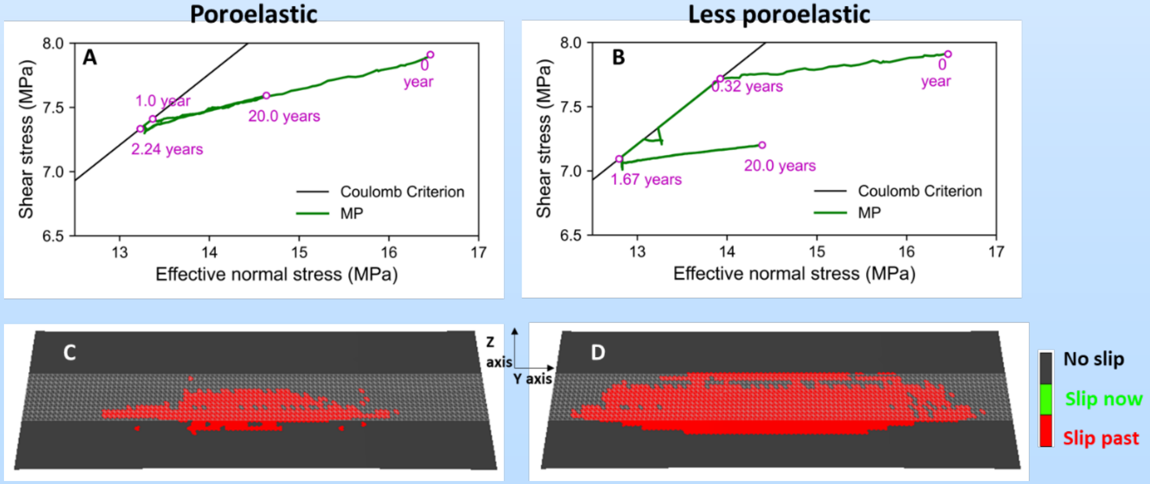


We find that the poroelastic effect is <u>limiting</u> the fault rupture

Our models at project and Basin scales generalize previous studies

15-20% POROUS
SANDSTONE/LIMESTONES
Biot coeff 0.6-0.8

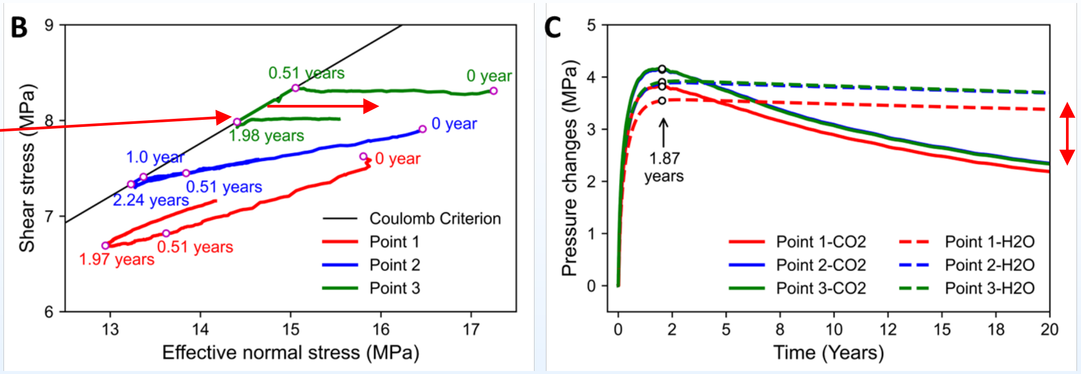
Less than 10% POROUS
Rocks/basement
Biot coeff 0.2-0.4



Effect of multiphase CO_2-brine flow

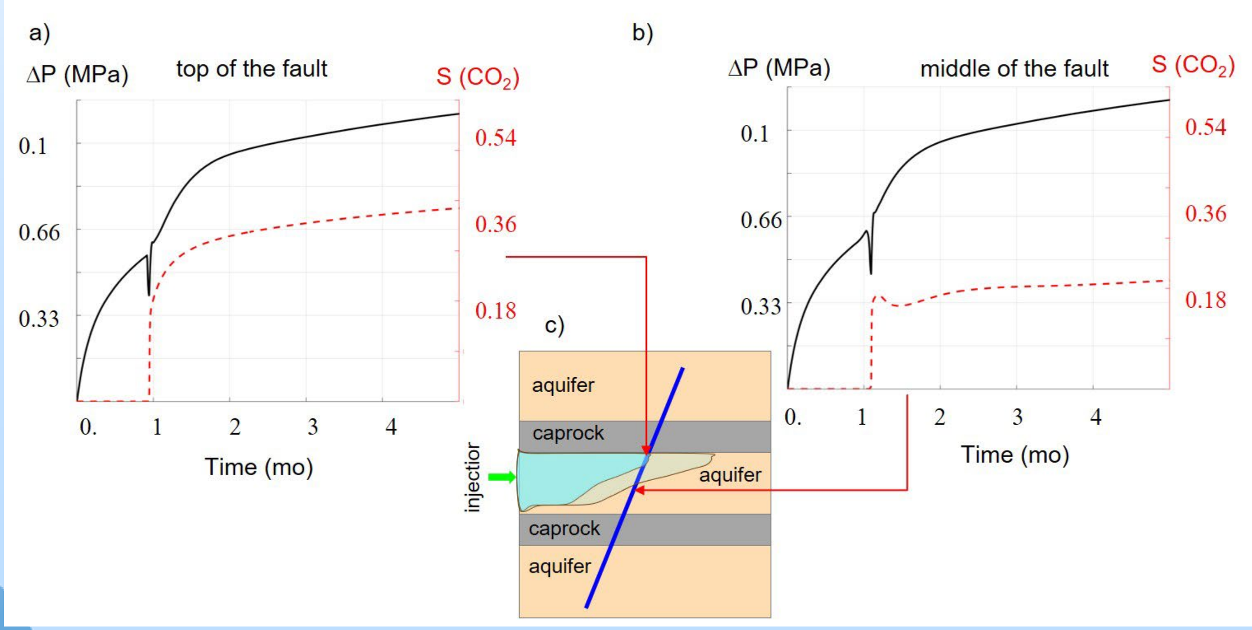
When enough CO_2 is stored in the system there is **a pressure relaxation that can “stop” faults rupture**

Re-Increase
In effective
Normal stress



Pressure relaxation
due to increase
in CO_2 mobility

But when CO_2 is “touching” the fault, some complex HM responses are observed
That could cause fault instability



Importance of Injection scenarios

High rates early followed by smaller rates leads to the Most rupture and seismicity

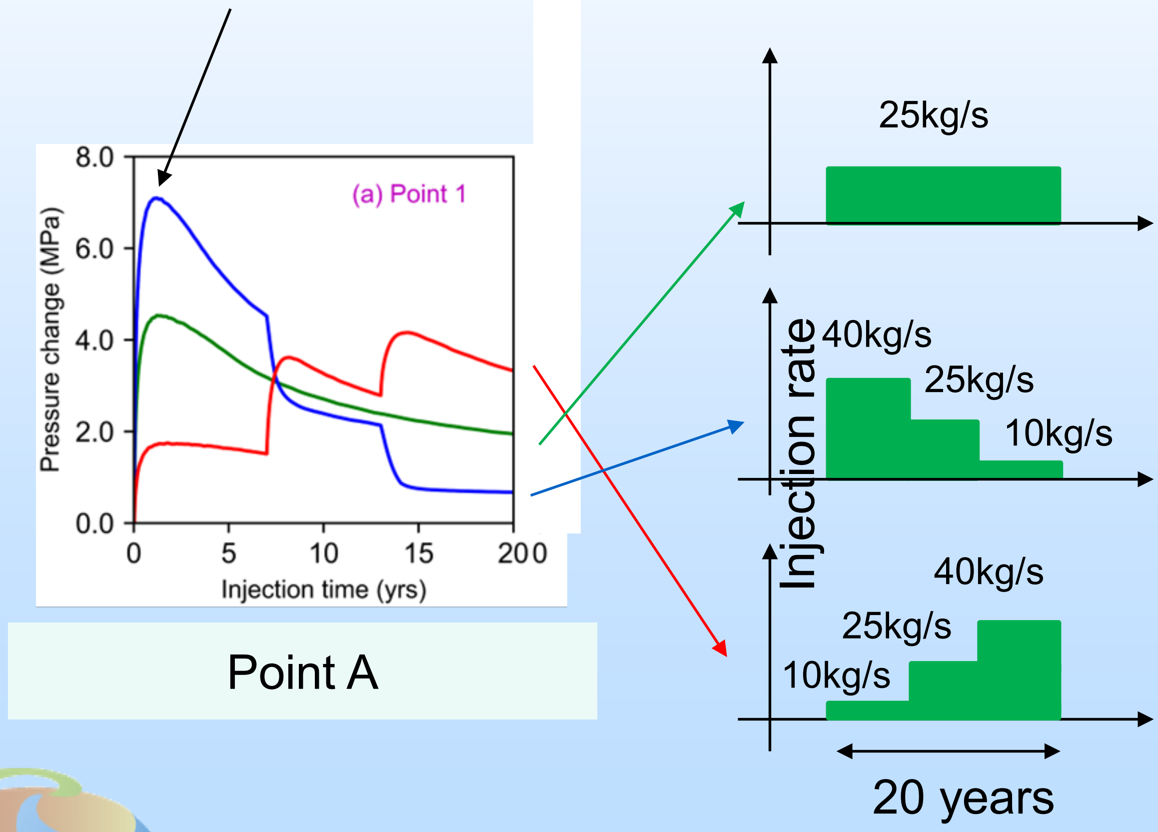
Effect of CO_2 mobility evolution with saturation

The higher the rate

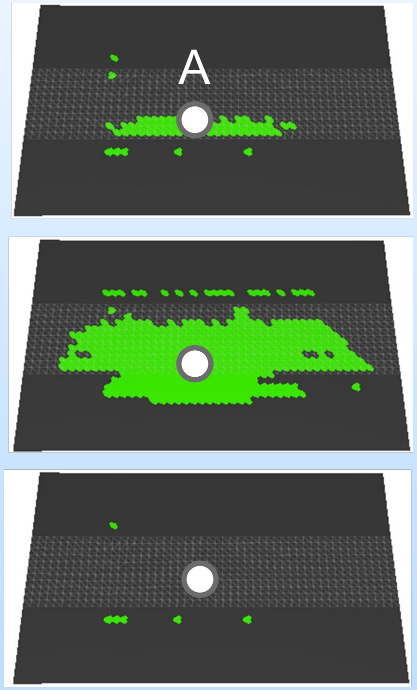
The higher the peak pressure

The larger the pressure decrease

For the same CO_2 volume injected over 20 years



Fault rupture after 20 years



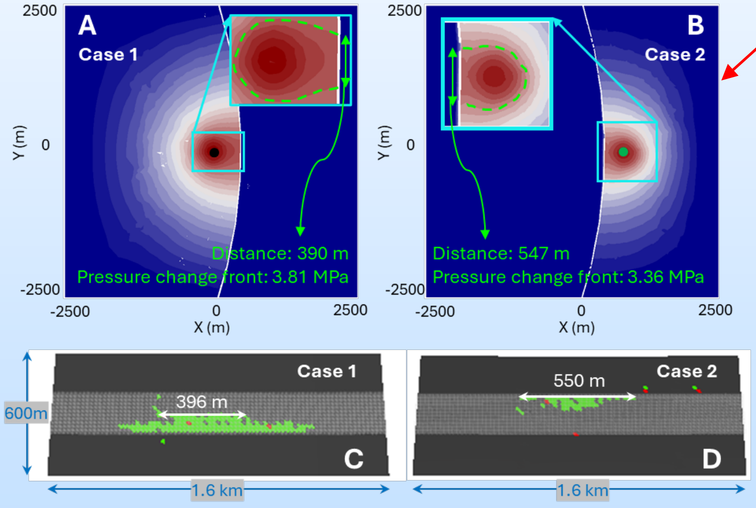
Well placement vs fault location

Example in a normal faulting regime

Results may change in a strike slip regime

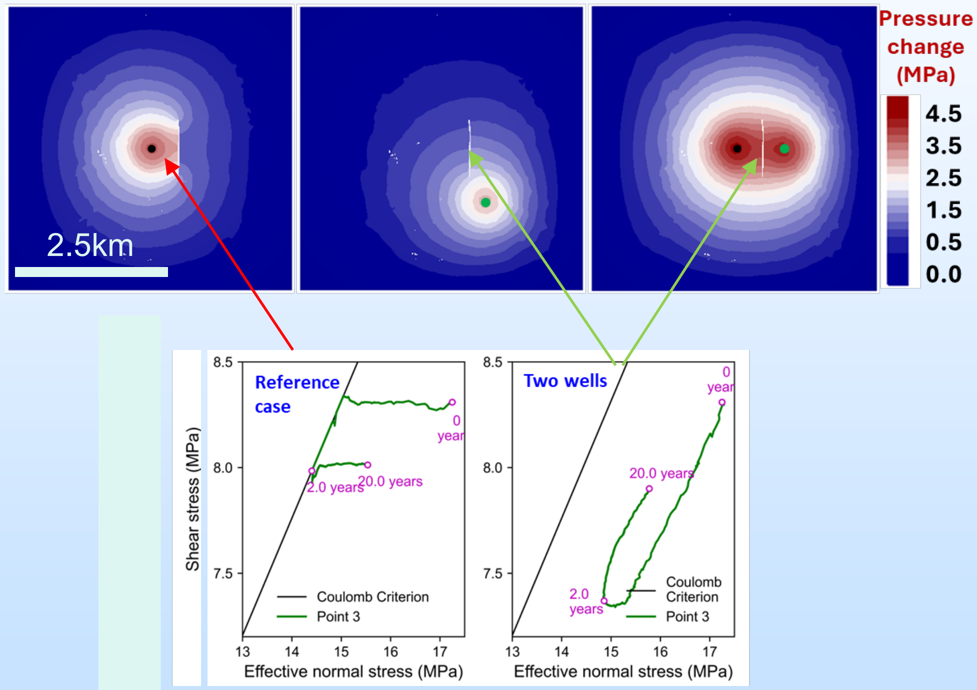
Risk of down-dip leakage
And seismicity

Risk of up-dip
Fault leakage



Failure

No Failure



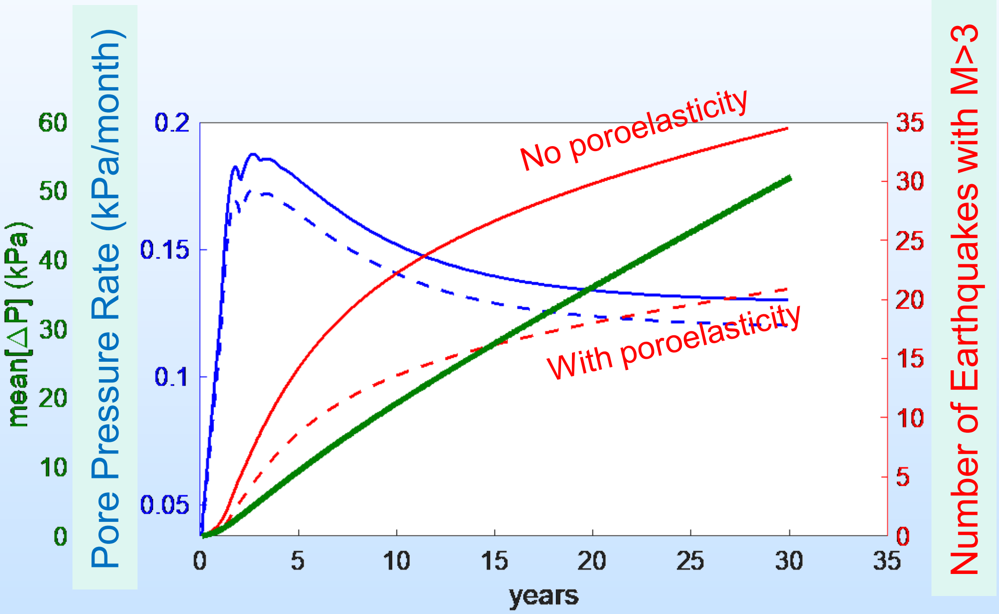
Effect of pore pressure rate and poroelastic stressing on deep-basement induced seismicity

- Using the large-scale 3D poroelastic model
- Oklahoma seismic catalogue as an analogue
- Empirical correlations between the seismicity rate and the basement pressure variation in the seismic zone

Modified Gutenberg-Richter law for injection induced earthquakes

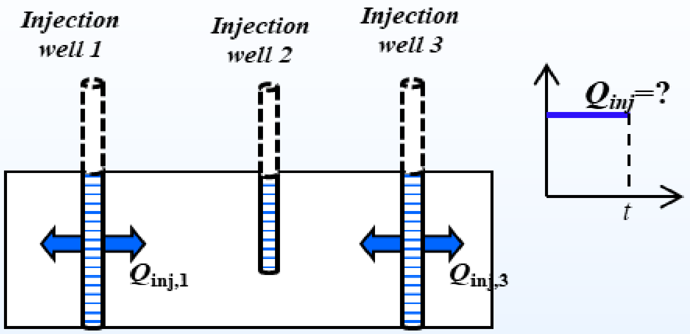
$$\underbrace{R_{\geq M}(\vec{r},t)}_{\text{Monthly earthquake rate}} = \underbrace{10^{a(\vec{r},t)-bM}}_{\text{Time and space dependent GR-law}} = \underbrace{[\Delta P_p(\vec{r},t)]^2}_{\text{Driving force}}\, 10^{\underset{\text{Seismo-tectonic state}}{\underset{\uparrow}{\Sigma_p(\vec{r})}} - \underset{\text{Magnitude scaling}}{\underset{\uparrow}{b}}M}$$

Langenbruch, Weingarten and Zoback, 2018
Nature Communications



Applying optimization algorithms

Optimization of injection rates



Maximize $f(\vec{x}_{inj},\vec{Q}_{inj}) = M_{inj}$

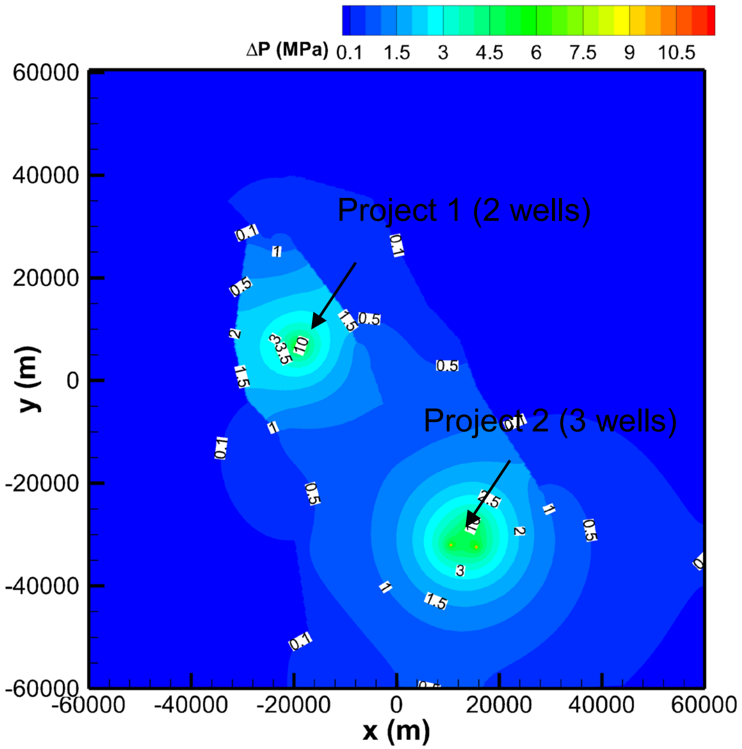
Subject to $g_1\left(\vec{x}_{inj},\vec{Q}_{inj}\right) = \max\{P\} < P_f\ (wells)$

$g_2\left(\vec{x}_{inj},\vec{Q}_{inj}\right) = \max\{\tau/\sigma_n'\} < \mu\ (fault\ segments)$

Testing Optimization Criteria

- Fracturing Pressure
- Coulomb pressure
- Additional criteria
- Distance of injection to first Coulomb failure
- Size/shape of failure patch relative to thickness of the caprock layer
- Time between injection start and first Coulomb failure events
- Increase in the background strain and/or pressure rates

Example case: Simultaneous injections from two project areas. Injection duration=20 y and injection rates are optimized to maximize injection mass and prevent fault slip and fracturing.

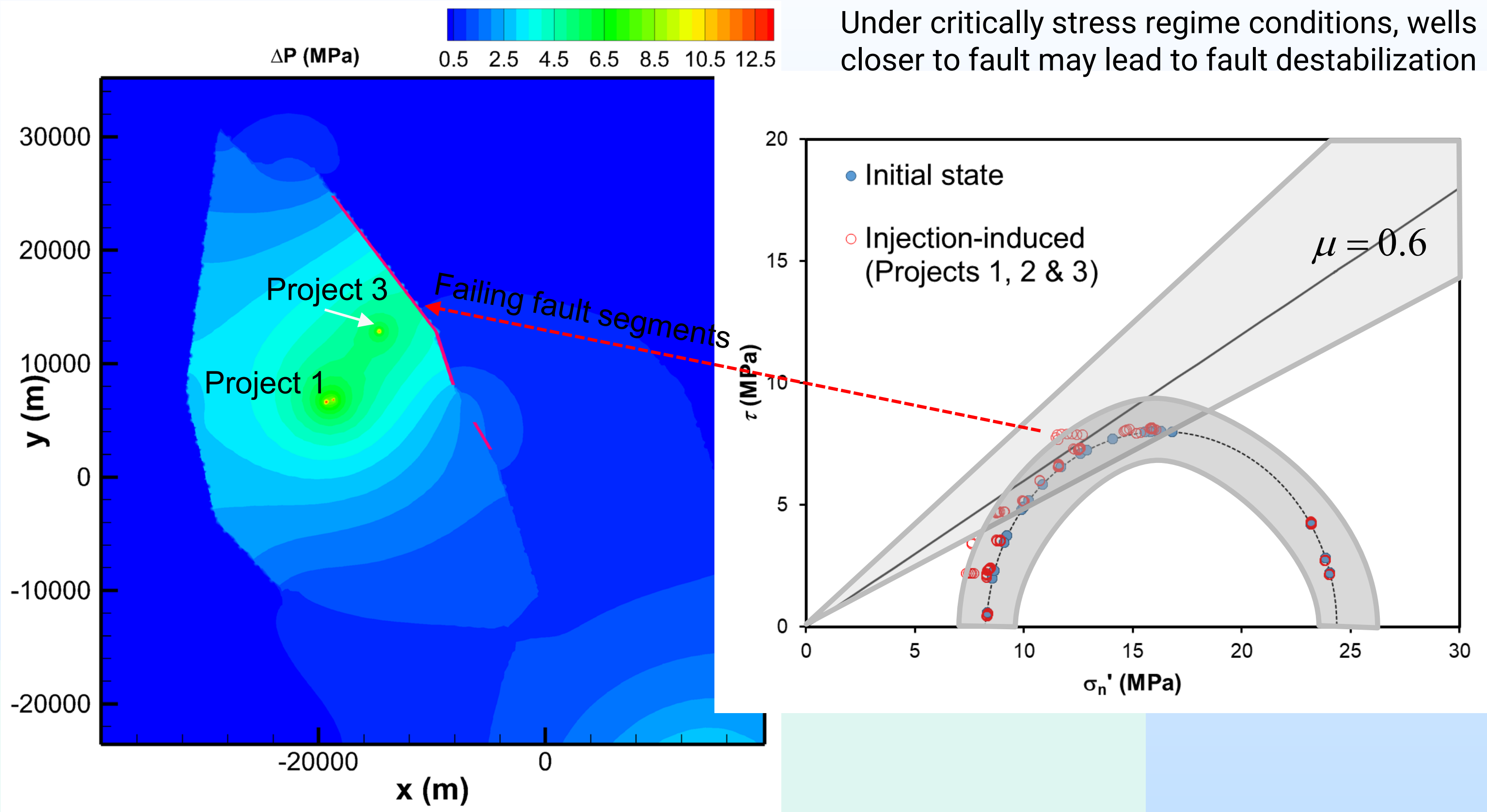


Must use adaptive management strategy !

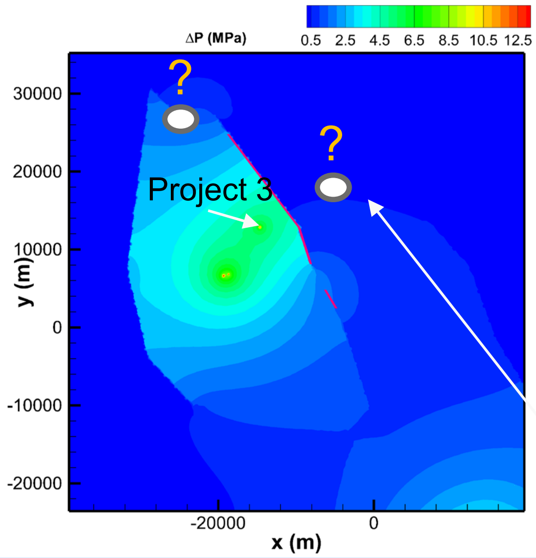
Example of a third project starting

in the previously optimized basin area with projects 1 and 2

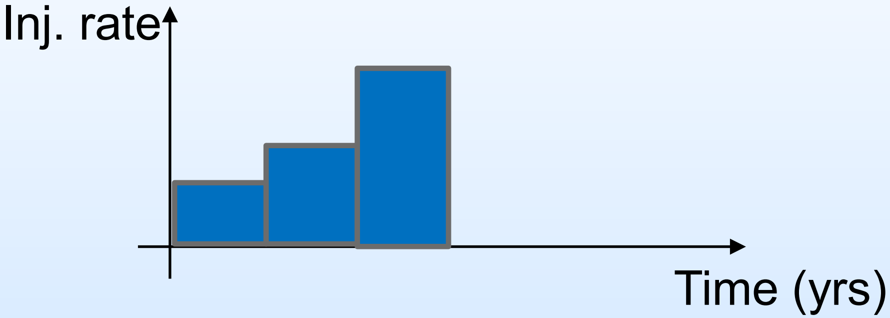
Under critically stress regime conditions, wells (Project 3) closer to fault may lead to fault destabilization



Potential management approaches to use at basin scale



1 – Reconsider optimization with 3 projects
Change injection rate and schedule at Project 3 or at all 3 projects?



2 – Relocate project 3
Strategic well placement (e.g., allow Project 3 to inject symmetrically from the fault or move project to fault tip

3 – Drill or use existing wells
To minimize pressure & stress changes via brine extraction

Accomplishments To Date

Strengthening processes

↗ Amount of stored CO_2

↗ Amount of poroelastic coupling

⇩

More Poroelasticity = More CO_2 stored and potentially less fault failure

⇧

Poroelasticity effect may be
High in the basin porous layers
Low in the basement

Weakening processes

1 - Changes in Background rates!
Pressure rate **– strain rate**

⇩

Higher pressure rates =
More fault failure and seismicity

2 - CO_2 touching an activated fault ?

Synergy Opportunities

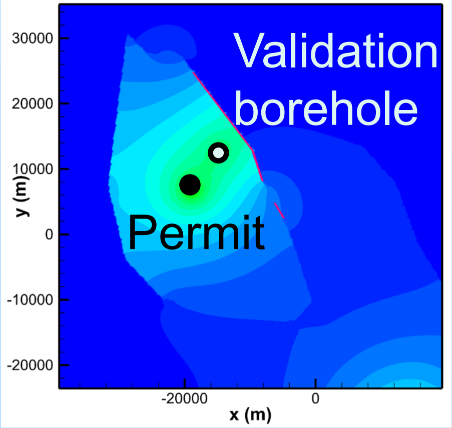
1 - Field scale MtTerri experiments (FWP-FP00013650)

Transfer knowledge on fault hydromechanical weakening/leakage

2 - One High Level Focus is to define NEW Monitoring Parameters in Optimization

Coupled Pressure and Strain **rate** – Seismicity (rate, location, Mag)

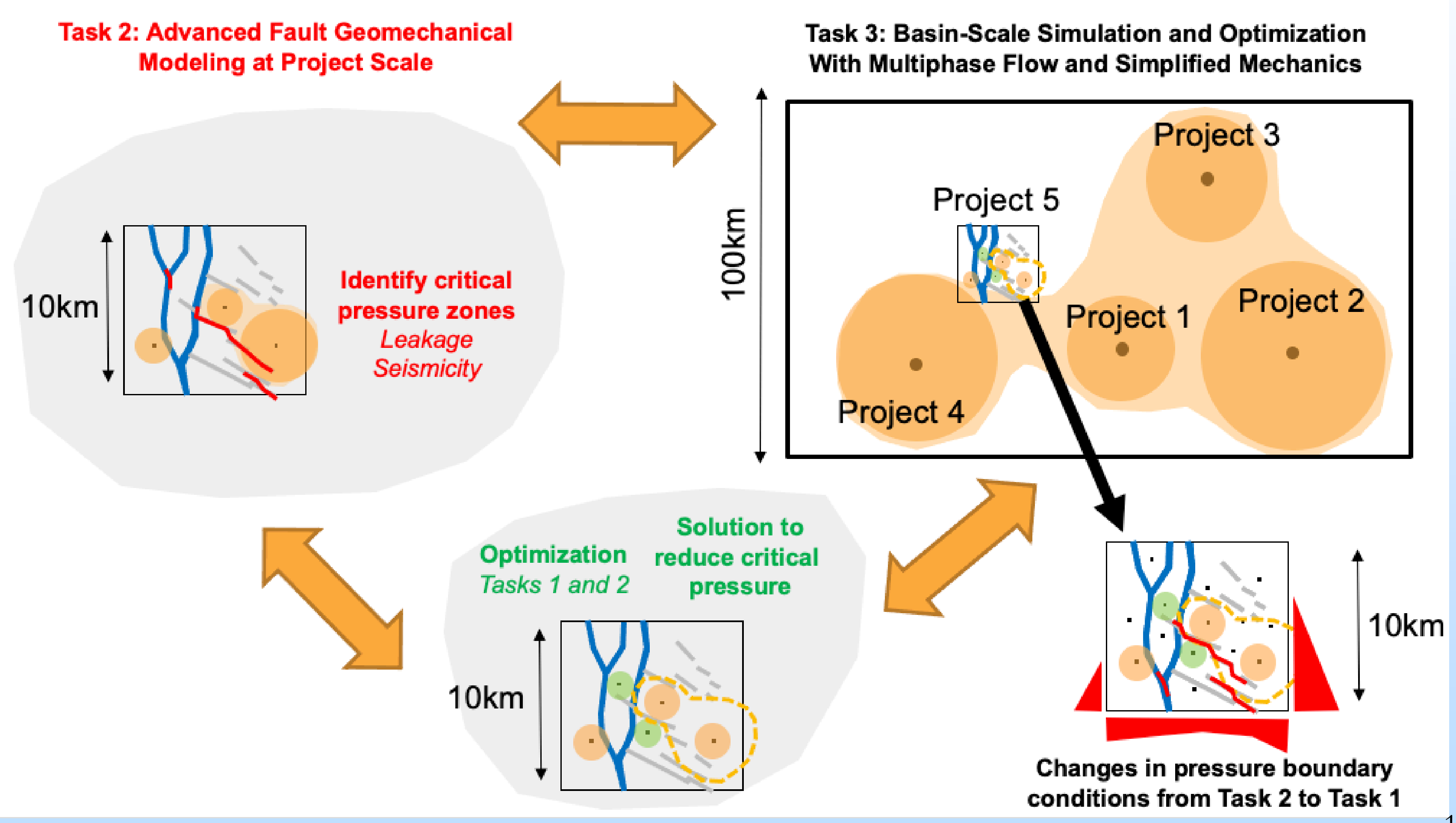
The Perspective would be to TEST these NEW Monitoring Parameters in a real Basin-scale field site



- CETPartnership 2023 proposal submitted
with NORCE Norwegian Research AS
Access to Horda platform multistorage Hub datasets
- **Need for a validation borehole!**

Backup Slides

Tight Integration Between Geomechanics and Basin-Scale Models



Task 2: Advanced Fault Geomechanical Modeling at Project Scale

Identify critical pressure zones
Leakage
Seismicity

Task 3: Basin-Scale Simulation and Optimization With Multiphase Flow and Simplified Mechanics

Optimization
Tasks 1 and 2

Solution to reduce critical pressure

Changes in pressure boundary conditions from Task 2 to Task 1

Appendix