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

(Field Work Proposal Number: FP00015629, FY23-FY25)

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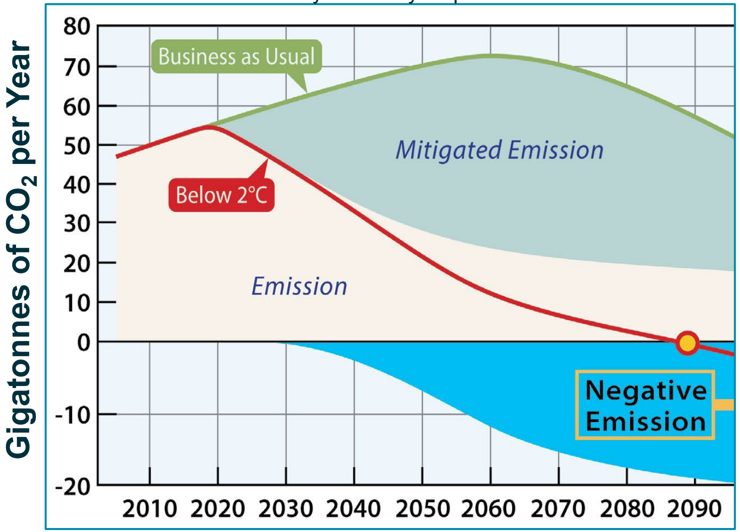
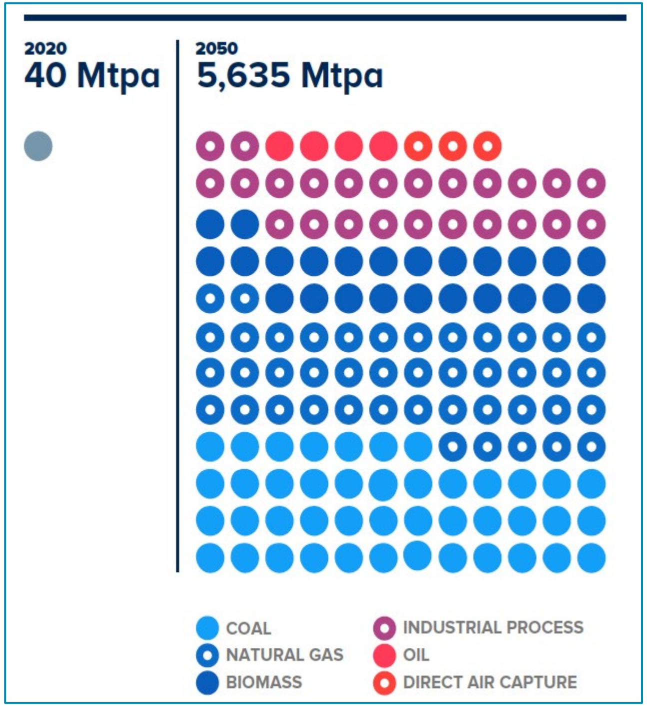
Motivation and Background

A Gigatonne CCS Future....

Royal Society Report

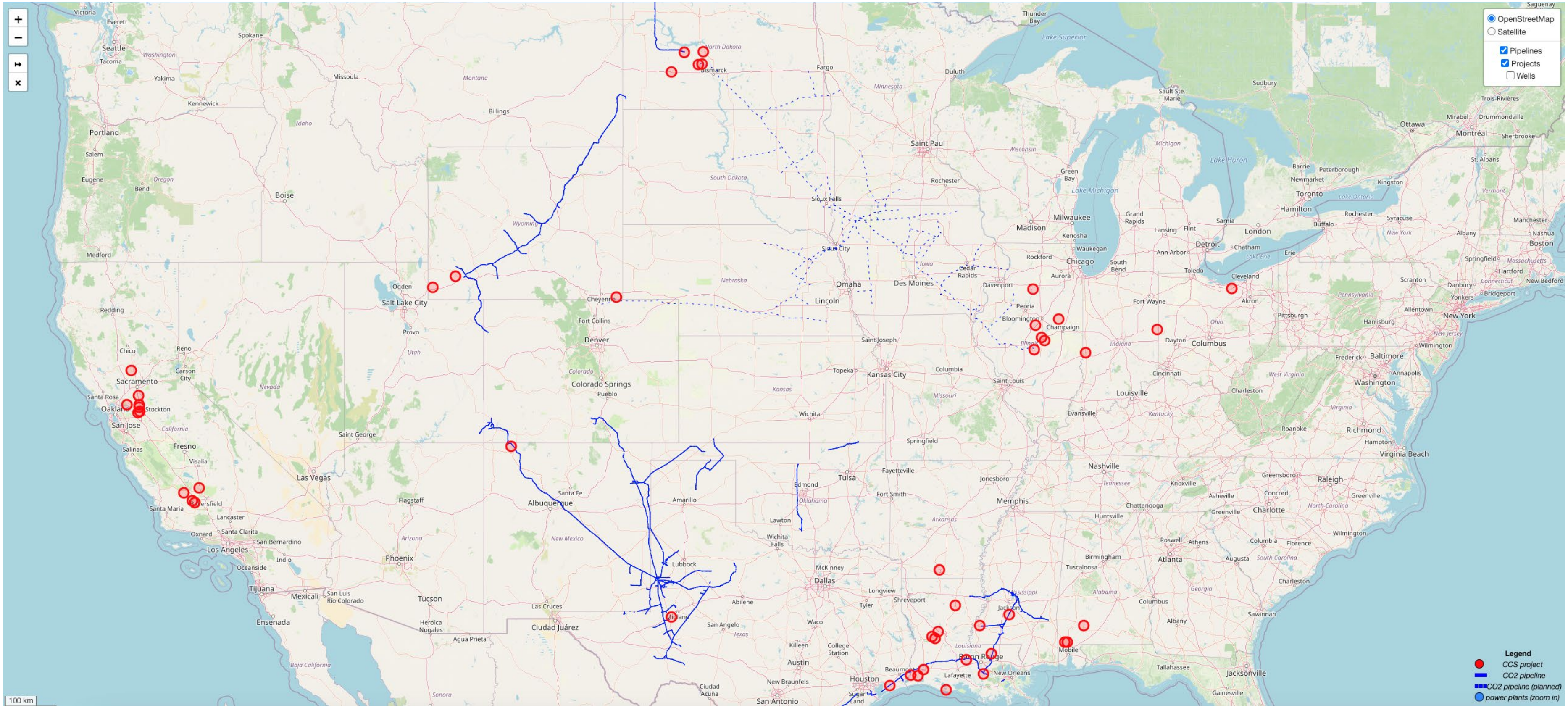


Global Status of CCS 2020, Global CCS Institute

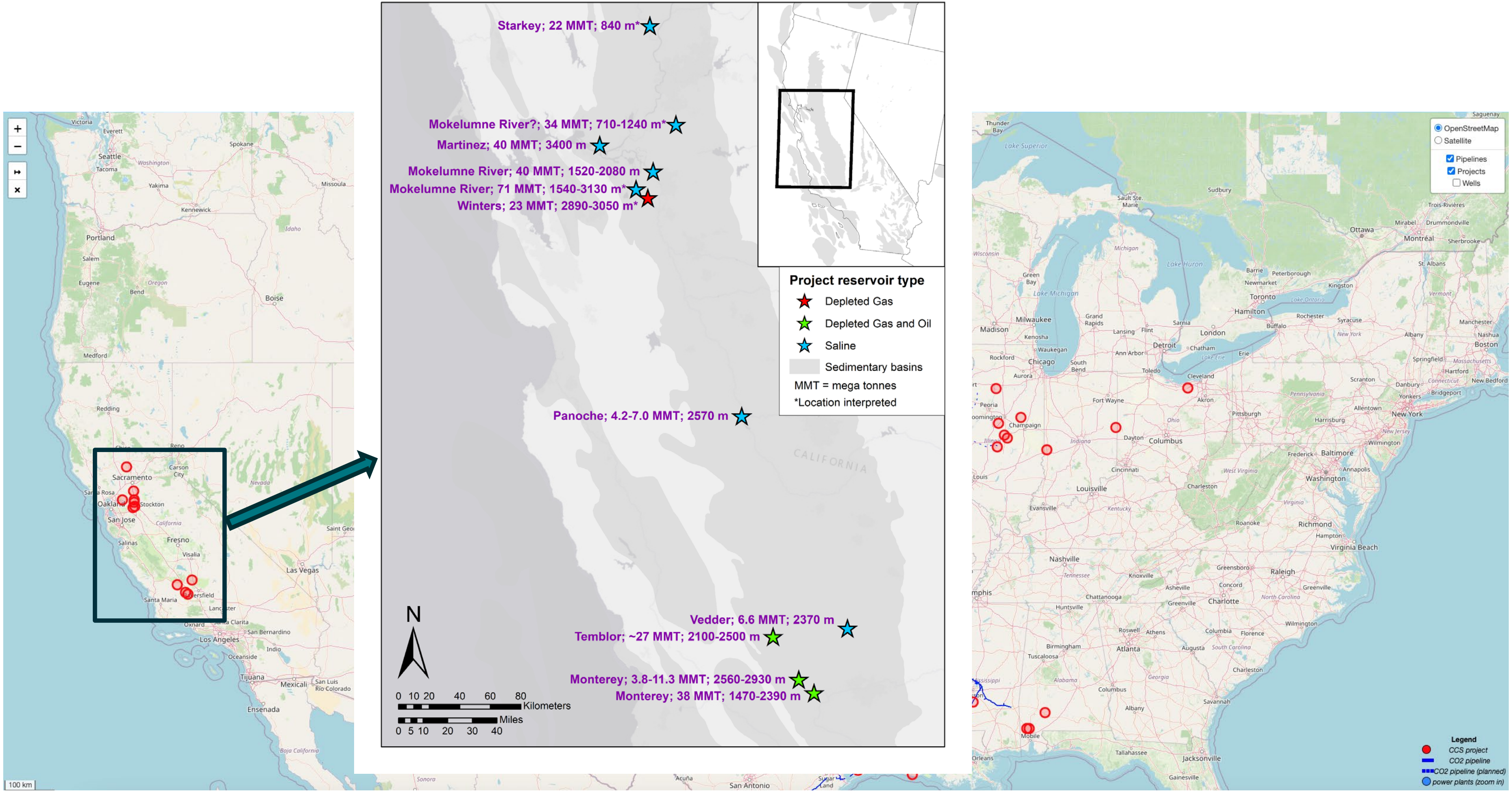


A Gigatonne CCS Future….Seems to be Starting Now

Status August 2023: More than 100 Class VI Permit Applications



Note: This status review is based on information provided by some but not all EPA regions.



Note: This status review is based on information provided by some but not all EPA regions.

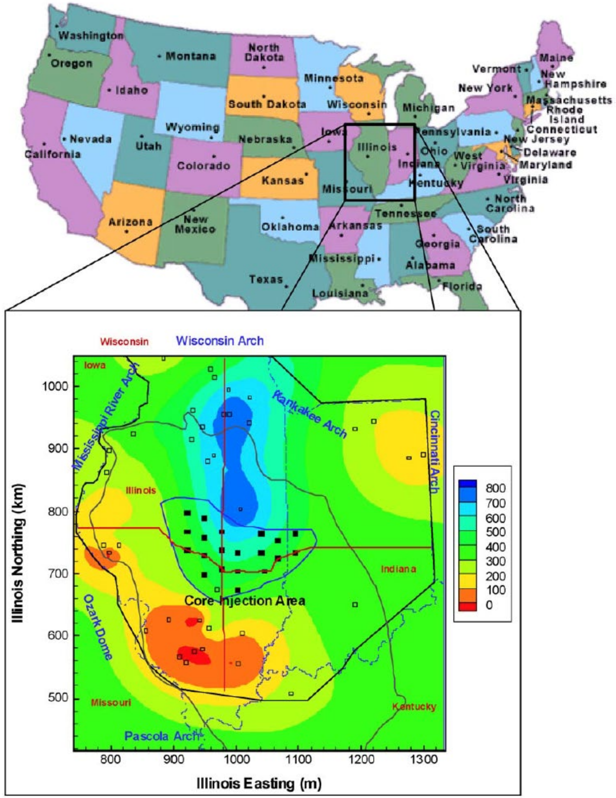
Evaluation of Potential CCS-at-Scale Impacts in 2009 IJGGC Paper

Study and Findings

- Modeling of a hypothetical CCS scenario in the Mt Simon in the Illinois Basin (20 projects at 5 M tonnes/yr).
- Results clearly illustrated possible cumulative effects, due to pressure interference between storage sites.

Recommendations

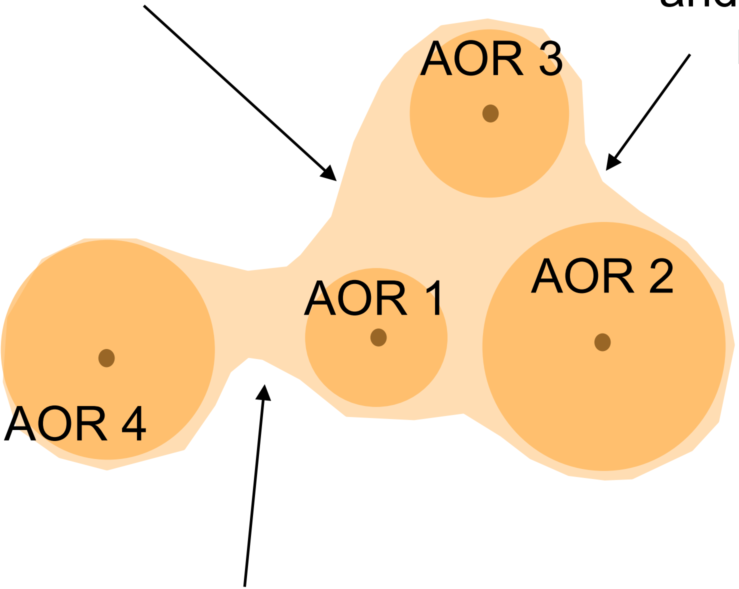
- Regional coordination may be needed in sedimentary basins with multiple sites.
- Far-field characterization and monitoring (beyond individual project areas) is important.
- Long-term basin-scale impacts can be informed by earlier site-specific monitoring.



Thickness of Mt Simon

Birkholzer and Zhou, IJGGC, 2009

Class VI Permit Applications: Cumulative Impacts



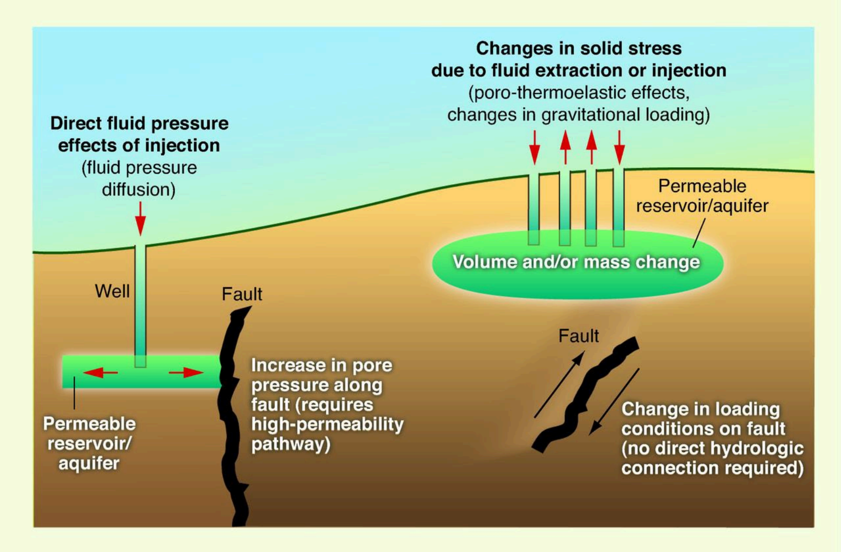
Cumulative AOR

Additional Characterization and Monitoring Needs?

Impacts on Project Risk and Permitting?

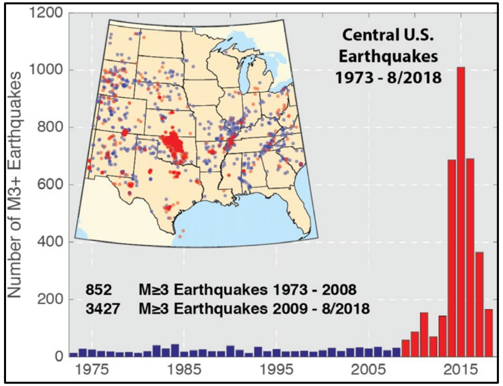
AOR = Area of Review

Induced Seismicity and Caprock Integrity Concerns in a Gigatonne CCS Future



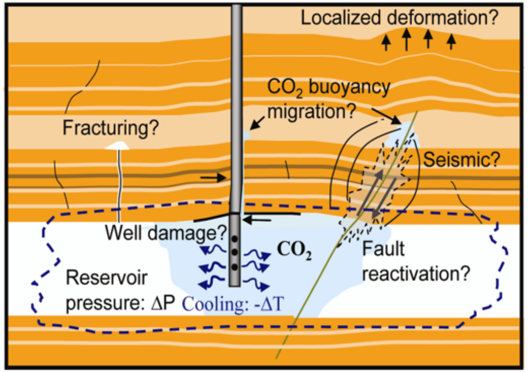
Ellsworth, 2013

Strong Earthquakes Triggered by Wastewater Injection



GSA Critical Issue Paper

Seal Integrity Issues and Potential Leakage Pathways



Rutqvist, 2012

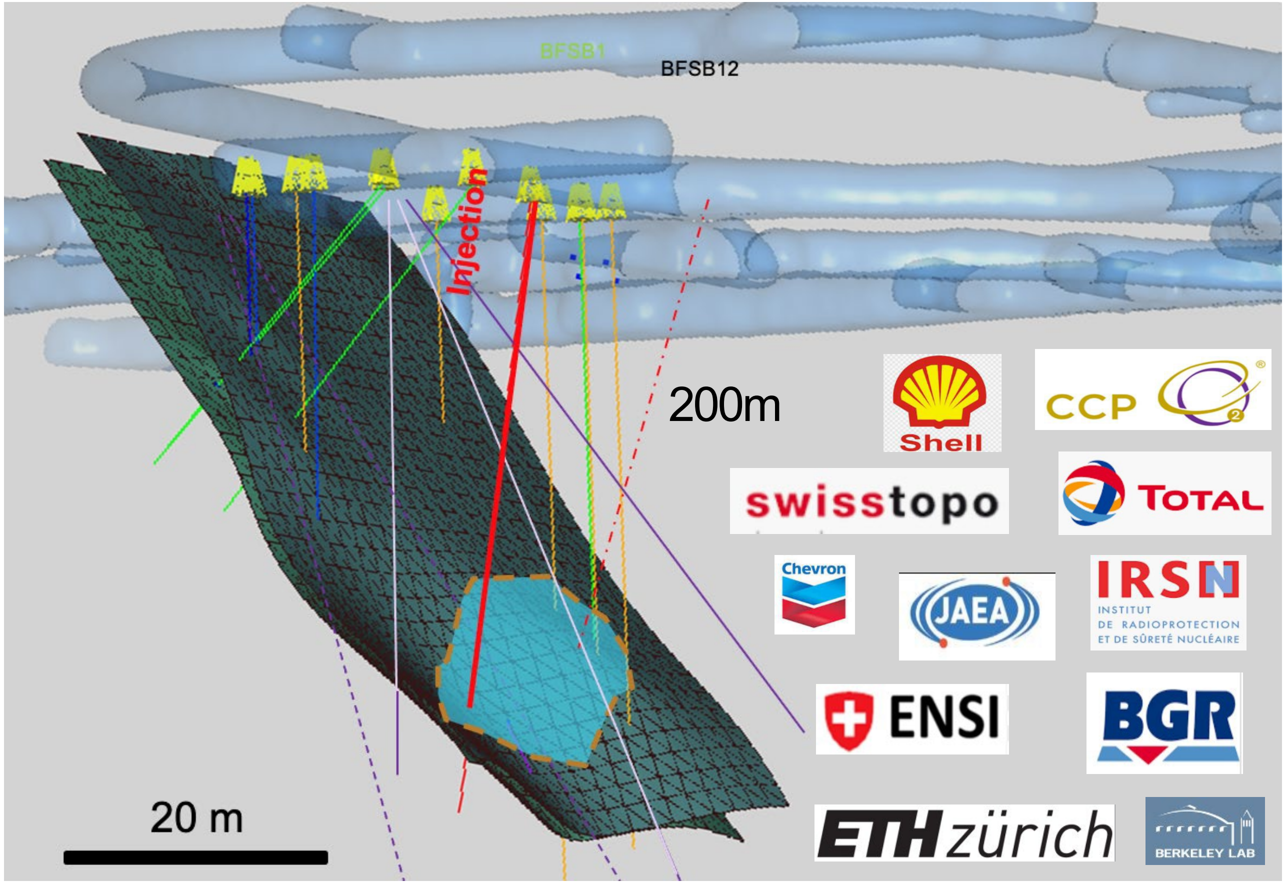
Understanding Seal Integrity:
Controlled Fault Injection Experiments (FWP-FP00013650)

2015 Kick-Off Experiment:
Fundamental geomechanical behavior of activated faults in a seal analog

2020, 2021, and 2023 Experiments:
Follow-up injection experiments with larger patch size, longer injection and post-injection cycles, and additional monitoring

Passive Observations:
Long-term post-injection evolution of fault permeability

Reactivation of shale faults can cause considerable permeability increase, as long as the pressure driving force remains.



Shell
CCP
swisstopo
TOTAL
Chevron
JAEA
IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
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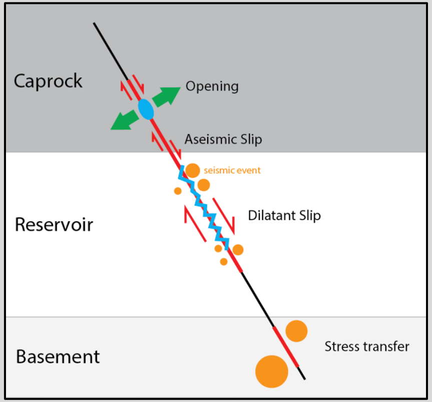
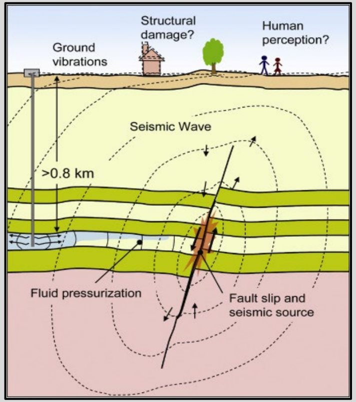
Project Objectives

Overall Objective: Develop a Framework for Basin-Scale Storage Optimization Based on Geomechanical Studies

Seal Integrity

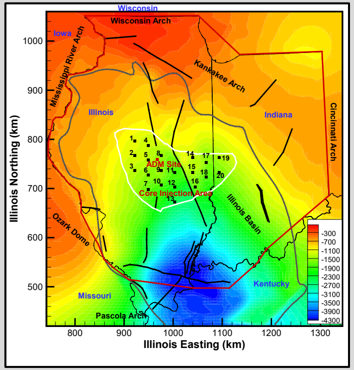


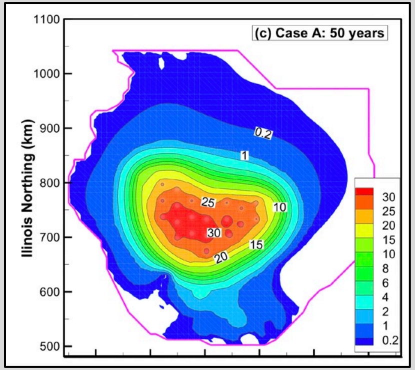
Felt or Damaging Earthquakes



Predicting Geomechanical Impacts

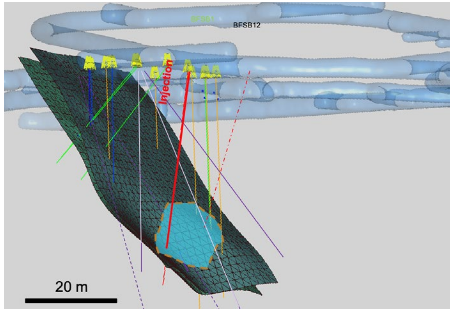
Assessing Basin-Scale Constraints





Key Objective 1 - Predicting Geomechanical Impacts

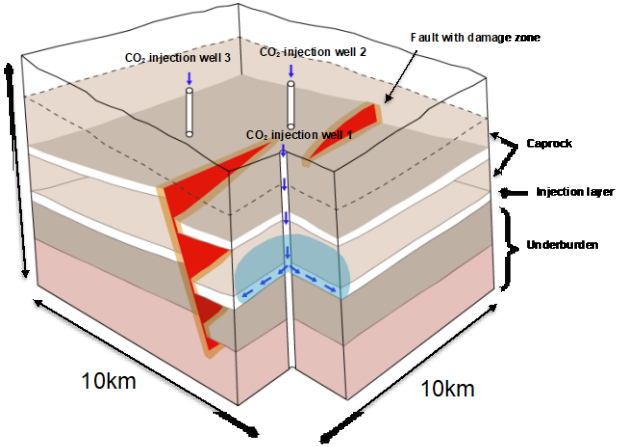
Transfer fault geomechanics knowledge derived from small-scale in-situ research experiments and/or pilot/demonstration to larger injection volumes and scales so that we can simulate with confidence important geomechanical effects at the scale of large storage projects.

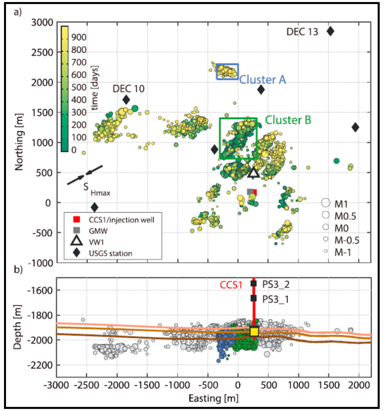


Mont Terri Fault Slip Studies (Cappa et al., 2022)

Meso-Scale Experiments

Predictions of Basement-Reservoir-Caprock Behavior at Project Scale





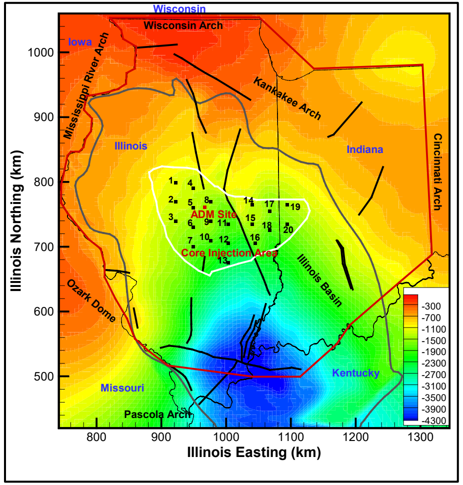
Decatur CCS1 Injection (Goertz-Allmann et al., 2016)

Demonstration Experiments and Analogs

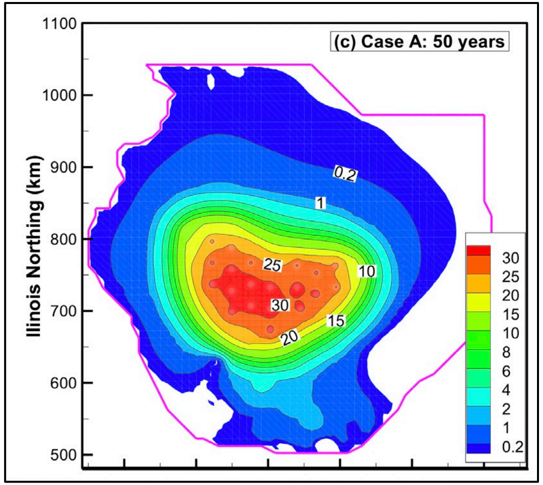
- Subtask 1.1: Identifying key physics of caprock, reservoir and basement faults
- **Subtask 1.2: Physics-based modeling of fault physics at the project scale**
- Subtask 1.3: Testing interferences between multiple CO_2 storage injections and faults
- Subtask 1.4: Knowledge transfer and handover to basin-scale models

Key Objective 2 - Assessing Basin-Scale Constraints

Gain a sound understanding of the basin-scale impacts (including geomechanical ones) 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.

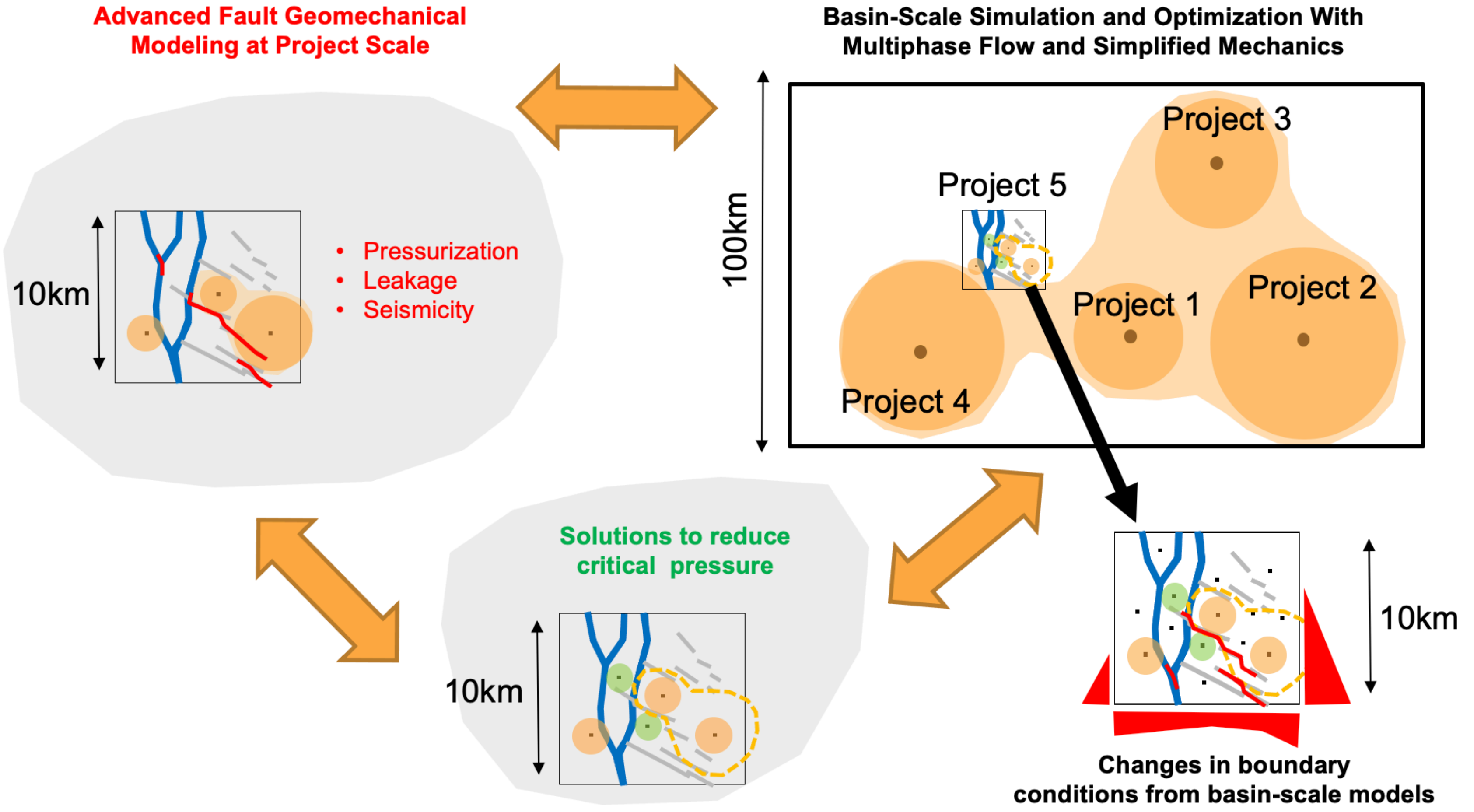


- ***Basin-scale flow models with simplified mechanics***
- ***Hypothetical scenarios for storage hubs and gigatonne CCS future***



- **Subtask 2.1: Develop computational framework for basin-scale modeling and optimization**
- Subtask 2.2: Apply the framework to generic basins and future storage scenarios
- Subtask 2.3: Assess strategies for optimized injection, brine extraction and monitoring
- Subtask 2.4: Handover of demonstrated framework to potential users

Integration between Geomechanical and Basin-Scale Models



Advanced Fault Geomechanical Modeling at Project Scale

- Pressurization
- Leakage
- Seismicity

Basin-Scale Simulation and Optimization With Multiphase Flow and Simplified Mechanics

Solutions to reduce critical pressure

Changes in boundary conditions from basin-scale models

Preliminary Activities
(Examples)

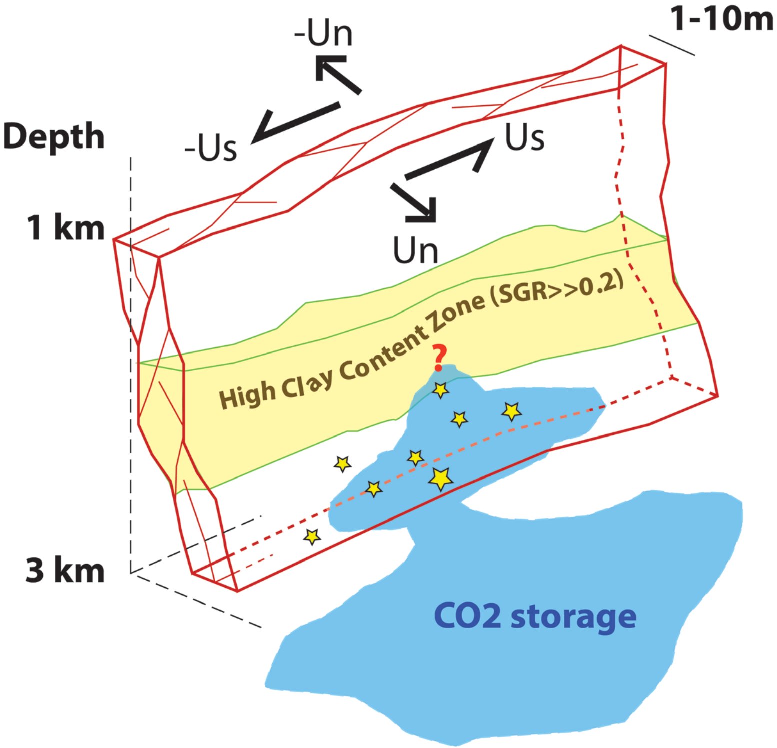
Geomechanics: Modeling Fault Physics at the Project Scale

Starting with a scenario observed in the field at Mont Terri and at basin scale (Eyre et al., 2019)

- **Can pressure increase in the storage reservoir activate slip on a fault that is rooted in the basement and intersects the overlying seal?**
- **Can such event lead to permeable pathways through the overlying seal?**

We use two complementary fully coupled numerical approaches:

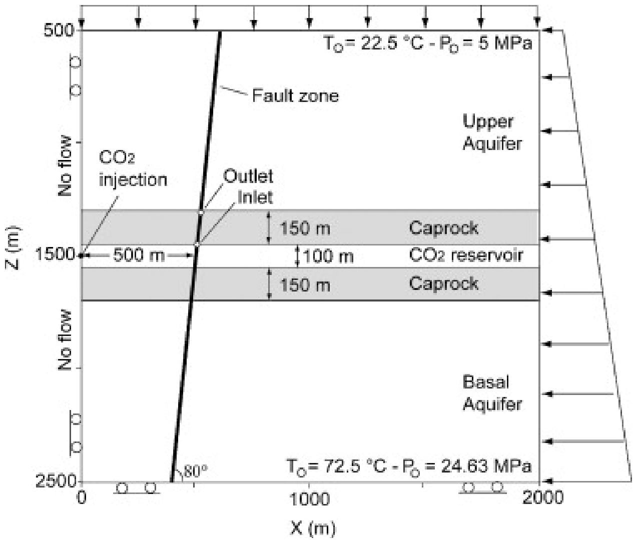
- **TOUGH-FLAC – THM solver with multiphase capabilities**
  Friction laws (Mohr-Coulomb with slip-weakening friction) and simplified seismic predictions (seismicity rate through an external python in house routine)
- **3DEC – HM solver single phase fluid flow**
  Friction laws (Mohr Coulomb with slip-weakening friction, rate-and-state, Cam-Clay) and advanced seismic predictions (earthquakes location, source parameters)

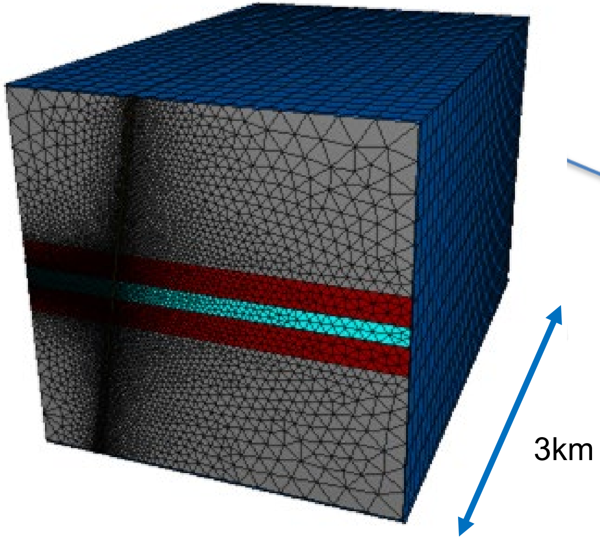


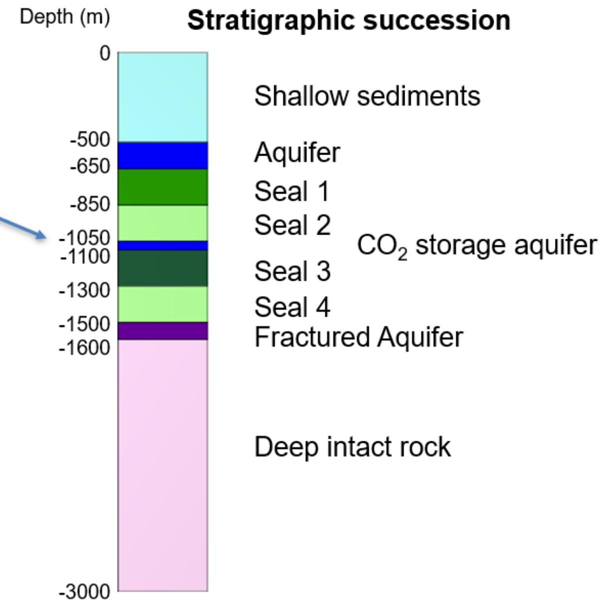
TOUGH-FLAC Modeling with Mohr-Coulomb & Slip-Weakening Friction

Starting with 3-D simulation of a single moderately permeable fault with homogeneous properties embedded into a 4 km x 6 km x 2 km volume

TOUGH-FLAC3D





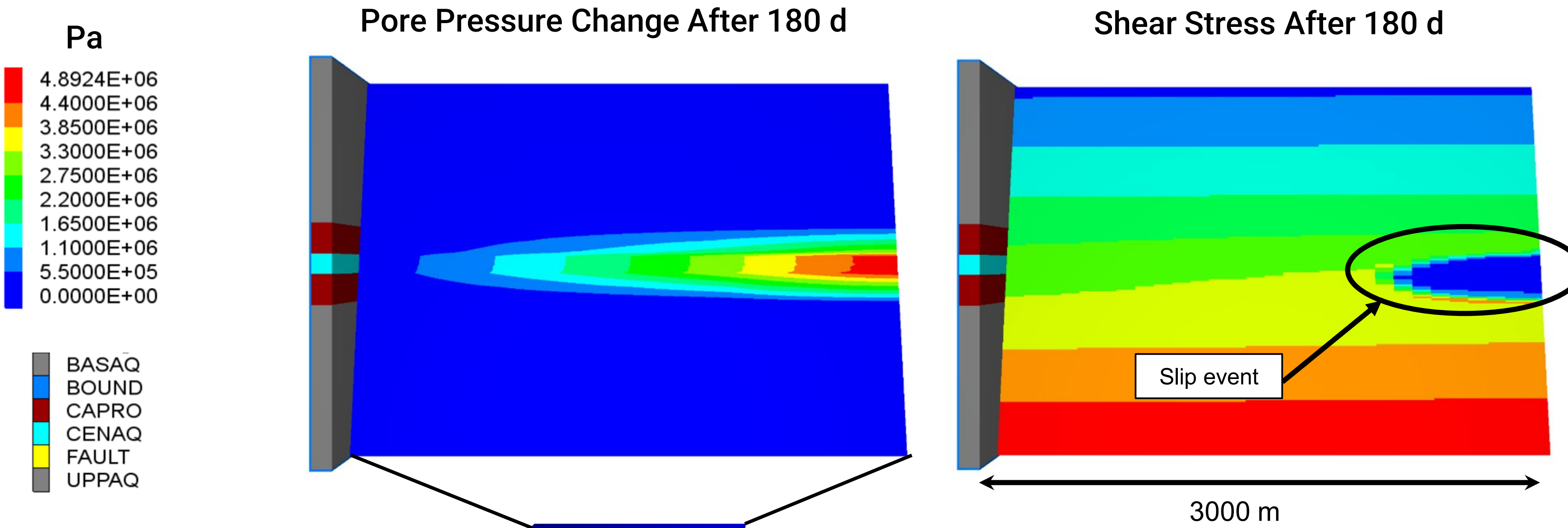


Model loading with a CO$_2$ injection rate of 2.5 million tons/year

Designed To Generate Fault Failure

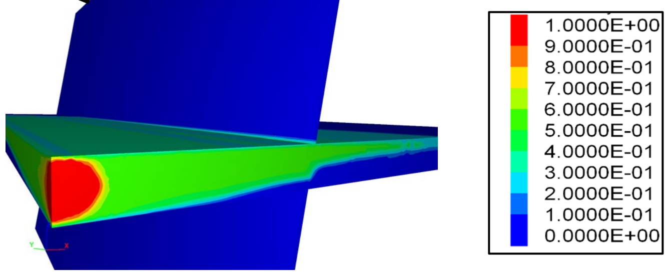
$$\tau \geq \tau_s = \mu_s \left(\sigma_n - P\right)$$

Shear Strength of the Fault Decreases Due to Pore Pressure Increase



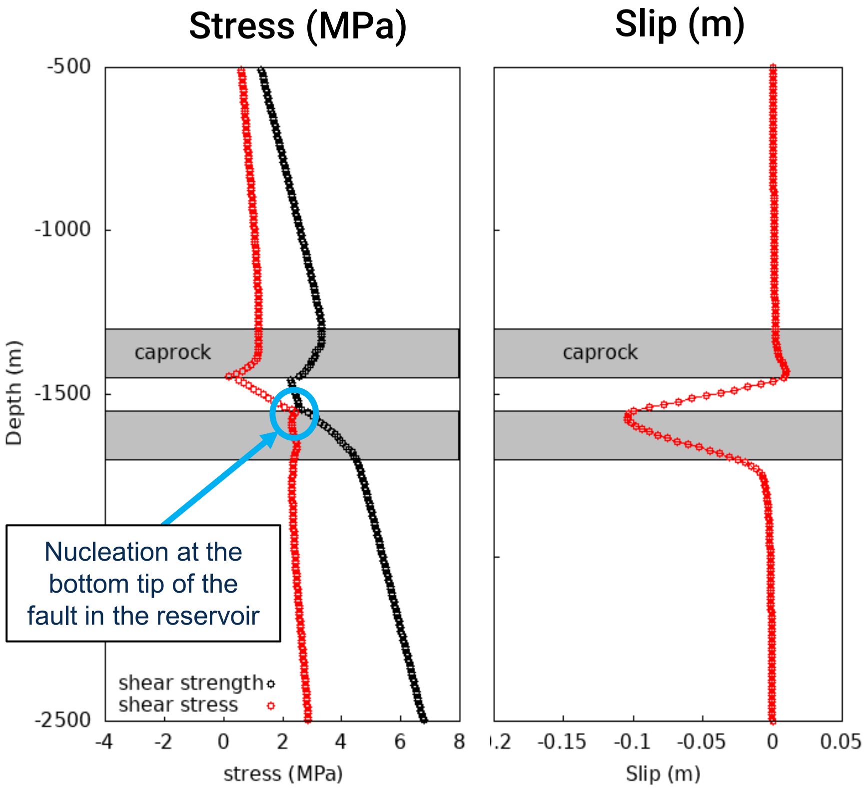
Pore Pressure Change After 180 d

Shear Stress After 180 d

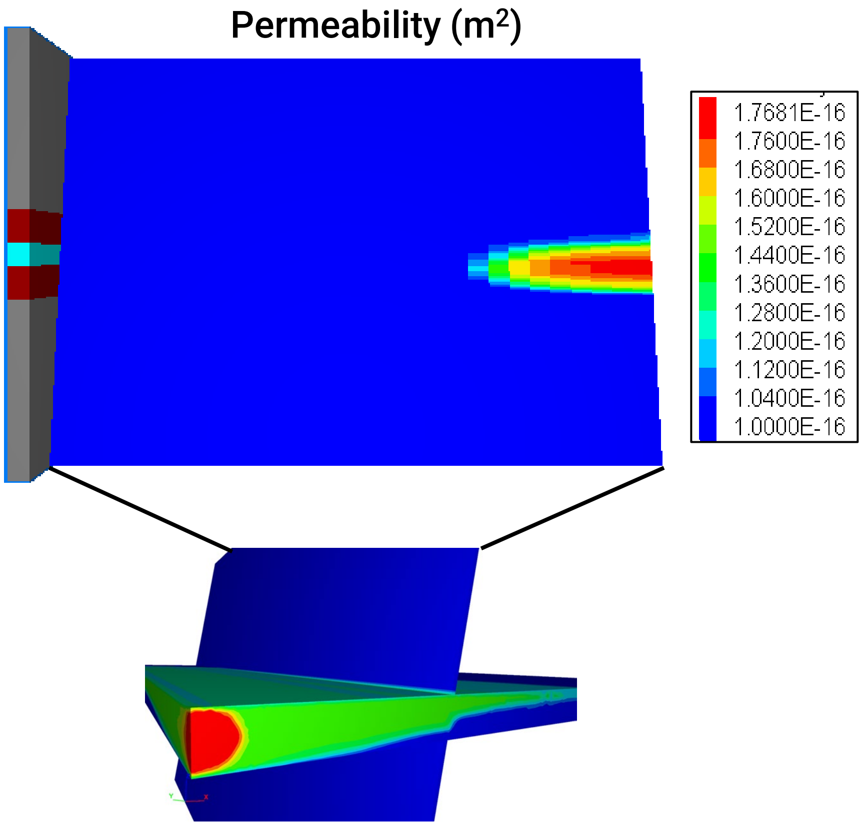


CO_2 Saturation

Failure Is Initiated At the Bottom of the Reservoir

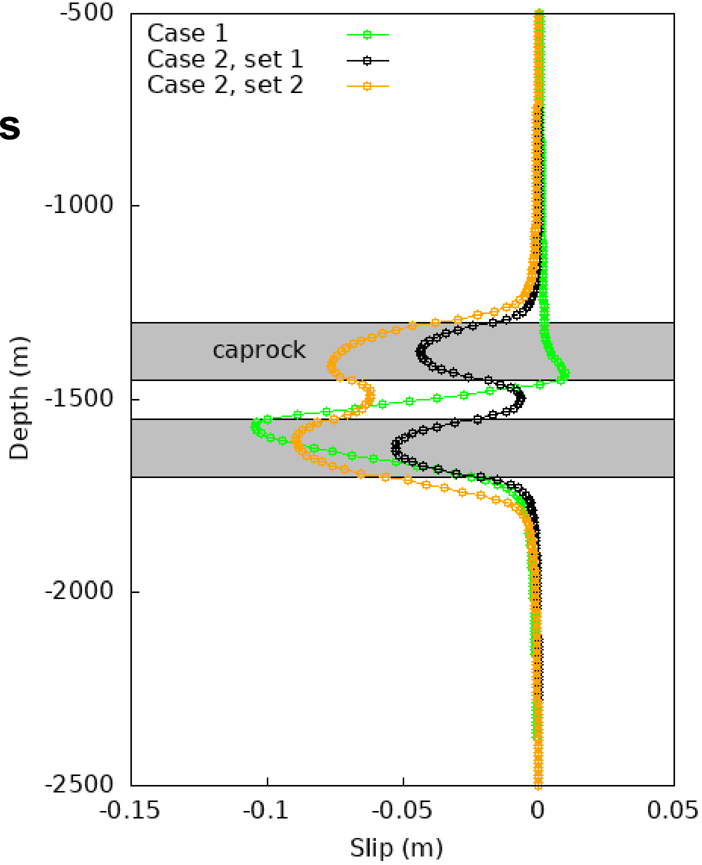


Nucleation at the bottom tip of the fault in the reservoir

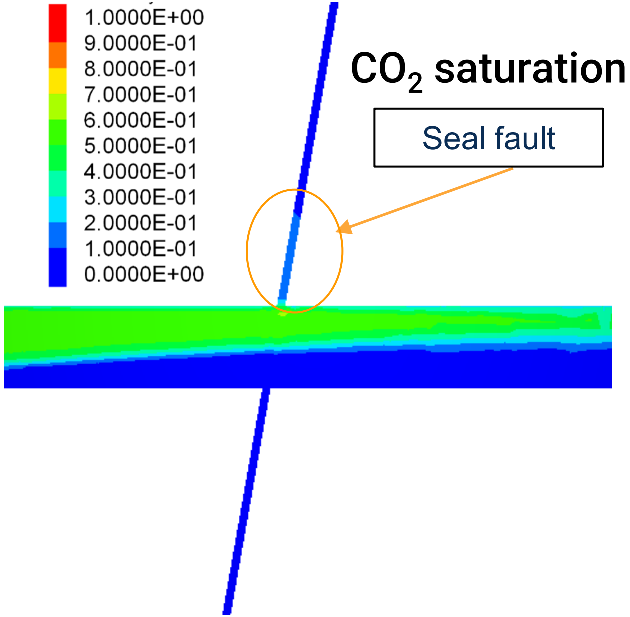


Heterogeneous Fault Properties Can Drastically Change Slip Behavior: Clay-Rich Fault Zones in Contact with Seal Layers

Heterogeneous with Clay-Rich Fault Zones in Contact with Seal (Black and orange)



Previous Case with Homogeneous Fault (Green)



Permeability in caprock fault increases *from ≈ 10^{-19} to ≈ 10^{-16} m^2*

Next Steps: Sensitivity Study and Complex Fault Scenarios

Influence of fault geology/geometry

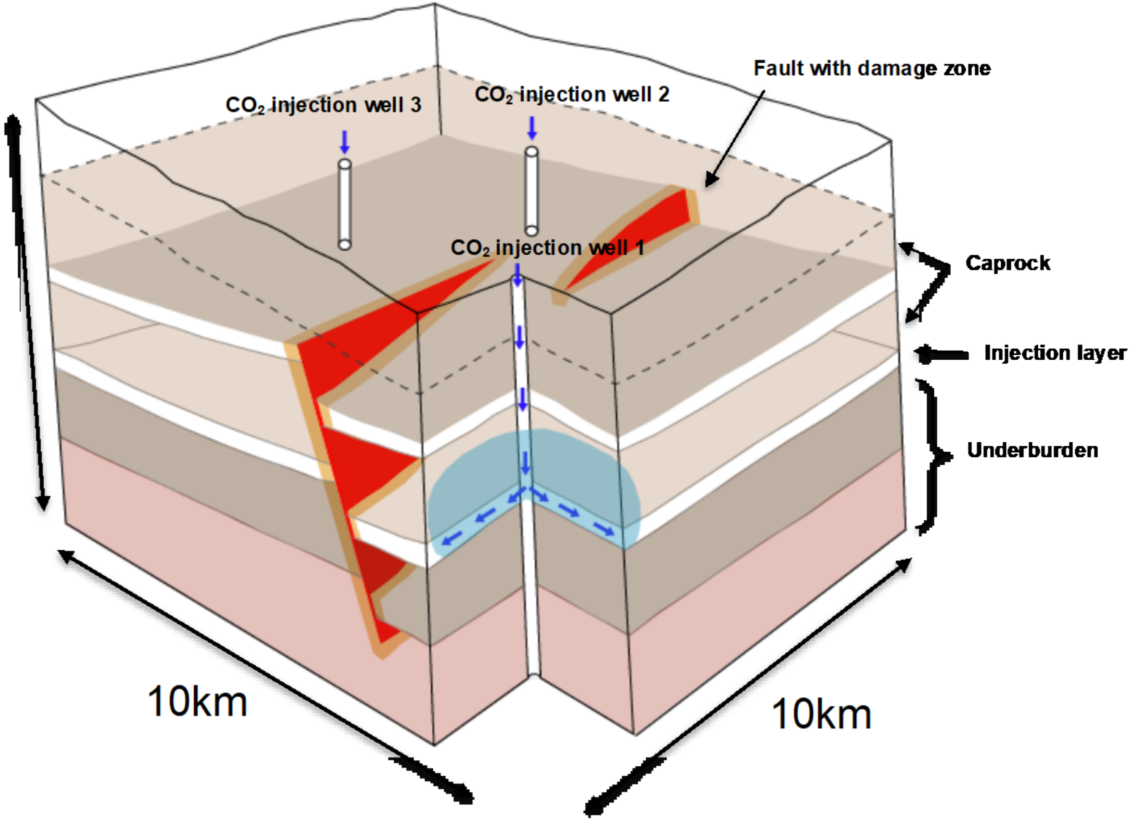
- Length, thickness, shape, throw distribution, offset
- Multiple faults
- Size and shape of the fault rupture patch
- Depth of the rupture

Influence of state of stress and its perturbation by basin layering

- Isostatic, normal regime, strike-slip, thrust regime
- Effect of tectonic strain rate
- Stress heterogeneity related to fault frictional heterogeneity and to vertical stress perturbations

Fault constitutive laws coupled to fault permeability

- Brittle behavior – Mohr-Coulomb with slip weakening and associated permeability law
    - Initial fault permeability + slip dependent permeability variation in reservoir and basement
    - No initial fault permeability + failure dependent permeability in caprocks
- Brittle-ductile behavior
    - Mohr-Coulomb (faults) and Cam-Clay (intact rock) to represent effect of matrix bulk ductility
    - Cam-Clay everywhere to explore fault ductility
    - Cam-Clay for sealing units, Mohr-Coulomb for reservoirs and basement
    - Rate and state for comparison



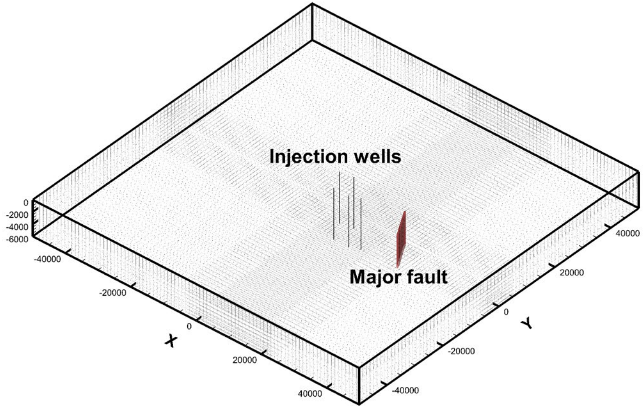
Basin-Scale: Develop Efficient Computational Framework

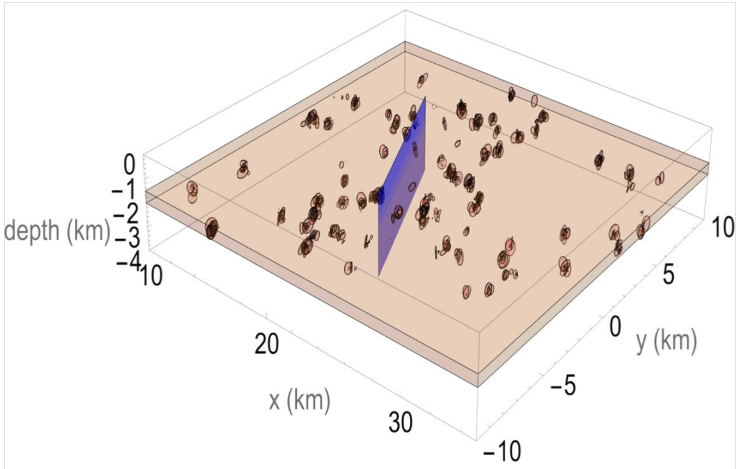
How to simulate pressure and geomechanical effects in large basins with multiple projects?

Semi-analytical Model (SALSA-Poroelasticity)

  - Multilayered poroelastic model to predict pressure changes and stress perturbations
  - Possible to extend the approach for including fault barriers and heterogeneities
  - **Best for automatic optimization studies**

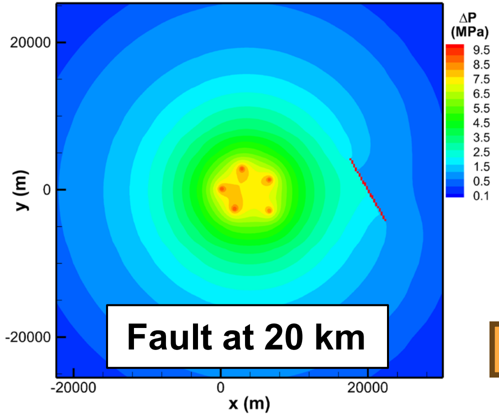
- **Simplified Numerical Model**
  - A 3-D coupled linear elasticity and flow model (Finite Volume Method-based)
  - **Best for basin-scale studies with multiple simulations needed (e.g., sensitivities)**
- **High Performance Full-Physics Simulation**
  - **Needed as ground truthing for simplified models**

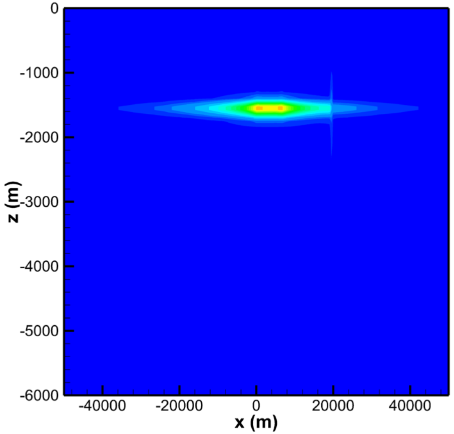


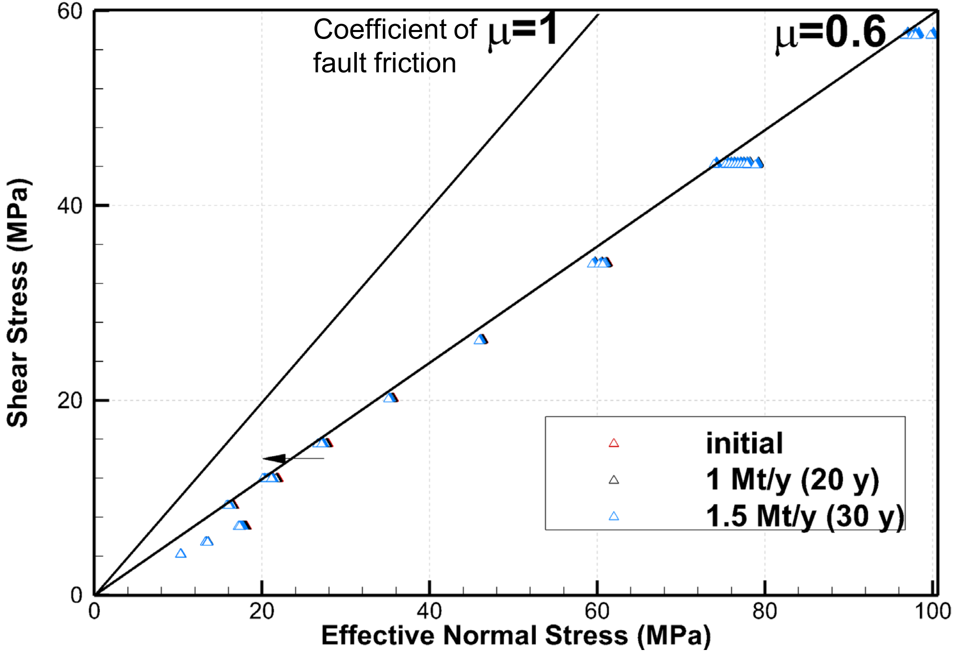


Example Application to a Generic Basin: Major Fault at 20 km

How much and for how long can be injected before the fault is activated?



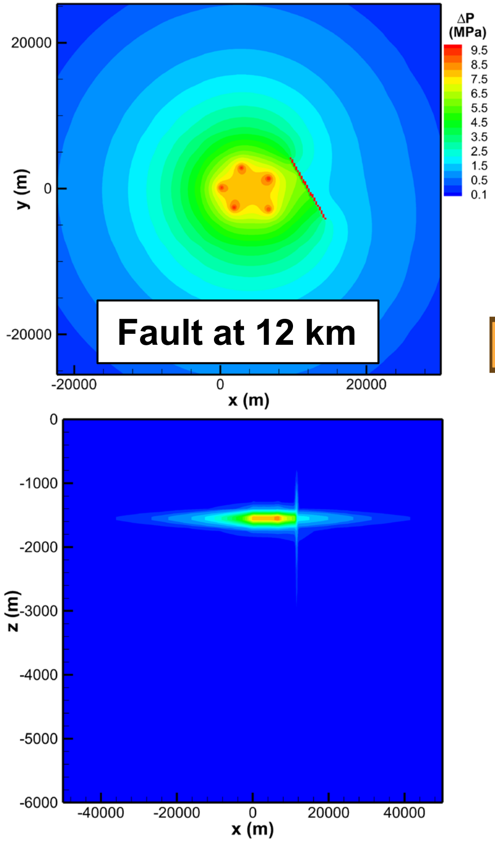


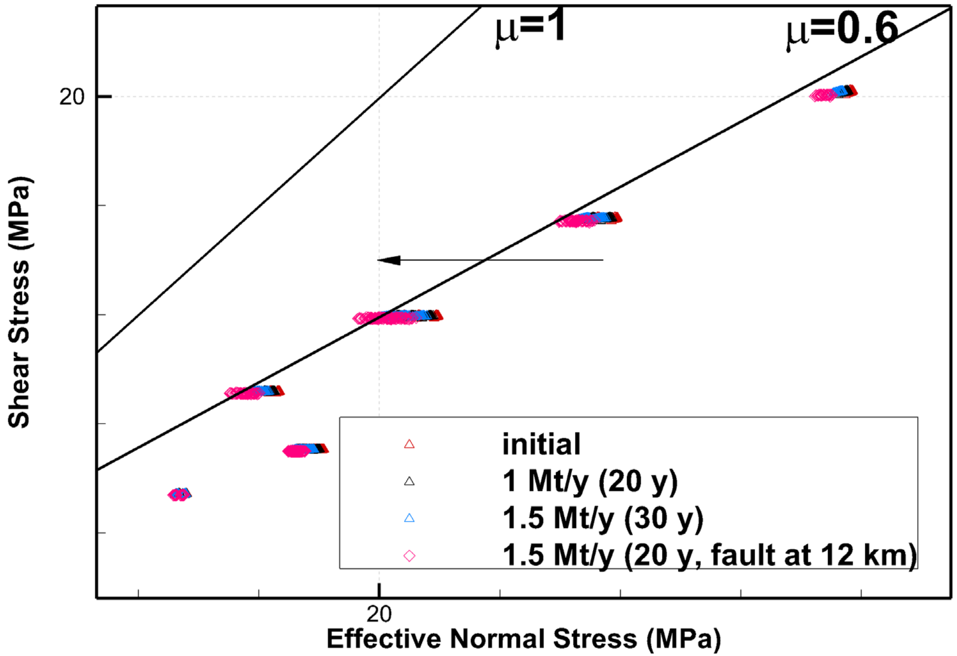


Fault permeability ~ 10^{-16} m^2
Inj reservoir perm ~ 10^{-13} m^2
Caprock perm ~ 10^{-18} m^2

Example Application to a Generic Basin: Major Fault at 12 km

How much and for how long can be injected before the fault is activated?





Fault permeability ~ 10^{-16} m^2
Inj reservoir perm ~ 10^{-13} m^2
Caprock perm ~ 10^{-18} m^2

Next Steps

- **Develop Computational Framework**
  - Continue development of simplified basin-scale poroelastic models with improved fault physics representation
  - Couple forward models with the optimization tools
  - Continue numerical experiments and compare results with full-physics simulations
- **Apply the Framework to Generic Basins and Future Storage Scenarios**
  - Examine basin-scale pressure impacts over a range of storage scenarios
  - Simulate geomechanical response for representative fault distributions
- **Assess Strategies for Optimized Injection or Brine Extraction**
  - Apply optimization tool and the developed models to explore basin-scale pressure management approaches for the selected basin systems
  - Explore basin-scale monitoring strategies

Wrapping Up

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Accomplishments to Date

Presented Today

- Conducted 3-D fault modeling at project scale, using Mohr-Coulomb with slip weakening friction and permeability change, and started with a comprehensive sensitivity study
- Developed and tested effective flow and simplified geomechanics approaches (analytical and numerical) for basin-scale simulation and optimization

Not Presented Today

- Finalized a comprehensive literation and data review, to identify key faults physics (reactivation mechanisms, permeability change) in reservoir, seal, and basement rocks
- Tested alternative fault modeling approaches using 3DEC and applied other constitutive relationships for fault reactivation (rate-and-state, Cam-Clay)
- Evaluated seismogenic index as an alternative handover mechanism between detailed geomechanics modeling and basin-scale assessments
- Started developing representative basin-scale CCS scenarios (based on existing hydrogeologic systems and expected CCS development in the US)
- Started conversations with EPA Class VI team

Thank you for your attention

Appendix

Key Team Members and Roles

Task 1: Project Management and Planning

- Jens Birkholzer, LBNL, Principal Investigator (PI)
- Susan Sprinkle, LBNL, Project Administrator

Task 2: Geomechanical Modeling

- Yves Guglielmi, LBNL, Co-Lead Task 2
- Jonny Rutqvist, LBNL, Co-Lead Task 2
- Frederic Cappa, Géoazur, University of Nice, Geomechanical Simulations
- Hafssa Tounsi, LBNL, Geomechanical Simulations
- Utkarsh Mital, LBNL, Geomechanical Simulations
- Meng Cao, new post-doc starting 9/1/2023

Task 3: Basin-scale Optimization

- Abdullah Cihan, LBNL, Co-Lead Task 3 for basin-scale optimization
- Matt Reagan, LBNL, Co-Lead Task 3 for basin-scale simulation

Cross-Cutting Task 2

- Stanislav Glubokovskikh, LBNL, Simplified Fault Mechanics to Inform Basin-Scale

Cross-Cutting Task 3

- Preston Jordan, LBNL, Representative Modeling Scenarios

Task 2: Geomechanical Modeling

Use the best-available experimental data/findings and new conceptual model/simulation approaches to assess CCS@scale scenarios

- Subtask 2.1: Identifying key physics of caprock, reservoir and basement faults

  We will first conduct a bibliographic review to extend the knowledge on the differences between basement, reservoir and caprock faults based on available field observations. This task will specifically include an attempt to generalize the Mont Terri experiment observations, and to isolate the key properties that must be considered to best describe the rupture and associated leakage potential.

- Subtask 2.2: Modeling fault physics at the project scale

  We will simulate the geomechanical response in basement, reservoir and caprock systems for a range of fault models and stress regimes, considering various injection scenarios. We apply continuum TOUGH-FLAC and discrete 3DEC models.

- Subtask 2.3: Testing interferences between CO_2 storage projects and faults

  We will test different project scenarios in order to explore under what conditions carbon hubs with large individual or multiple interfering projects may trigger fault seismic instability and leakage. We will consider a modeling portfolio of synthetic CO_2 injections scenarios and hydrogeomechanical conditions representative of actual field situations.

- Subtask 2.4: Knowledge transfer and handover to Task 3

  We will translate the sophisticated geomechanical simulations for use in Task 3. The simplest handover to the basin-scale storage optimization in Task 3 would be geomechanical constraints (such as maximum pressure) in critical zones with fault structures that would be prone to seismic rupture and/or caprock leakage if the maximum pressure was exceeded. At the next level of sophistication, we plan to upscale the complex physics of minor invisible faults as well as major seismically visible faults to generate a set of a priori distributions of the geomechanical risks.

Task 3: Basin-Scale Simulation and Optimization

Gain a rigorous understanding of the basin-scale impacts of a gigatonne CCS future, and develop a flexible and demonstrated simulation and optimization workflow that can be handed over to institutions tasked with regional CO_2 storage hub planning

- Subtask 3.1: Develop computational framework for basin-scale modeling and optimization

  We will first identify efficient flow and geomechanics models of varying fidelity that can be used with reasonable accuracy for the basin-scale optimization studies. We will also generate an updated optimization framework/code with new stochastic algorithms that are linked to these computationally efficient forward models selected.

- Subtask 3.2: Apply the framework to generic basins and future storage scenarios

  We will evaluate how multiple projects in large basins can be best deployed spatially and temporally to meet the demands of massive CCS deployment, considering basin-scale geomechanical effects.

- Subtask 3.3: Assess strategies for optimized injection as well as brine extraction

  We will assess how basin-scale scenarios with very large pressure increases and high geomechanical risks can be managed by smart spatiotemporal optimization of injection and extraction wells. The subtask will inform how to place brine extraction and injection wells in the basins with minimized number of wells and extracted brine.

- Subtask 3.4: Handover of demonstrated framework to potential users

  We will explore how the demonstrated simulation and optimization workflow for basin-scale optimization can be used by institutions tasked with regional CO_2 storage hub planning. Two options will be tested with selected planning institutions as follows: (1) The first option is to transfer the basin-scale models initially developed by LBNL for further use by the basin-scale planning institution. (2) The second option is to task LBNL, and other national labs, with the development and execution of basin-scale simulation in support of the planning institution.

Gantt Chart with Milestones and with Go/No-Go Decisions

Task	Milestone Description*	Fiscal Year 2023				FY24	FY25	Planned Completion (Reporting Date)	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		Q1	Q2	Q3	Q4						
Milestone 2-1 (A)	Title: Identifying key physics of caprock, reservoir and basement faults			X				Jun 30, 2023 (Jul 31, 2023)			
Milestone 2-2 (B)	Title: Physics-based modeling of fault processes at the project scale					X		Mar 31, 2024 (Apr 30, 2024)			* Go/No-Go decision
Milestone 2-3 (C)	Title: Testing interferences between CO_2 storage projects and faults						X	Dec 31, 2024 (Jan 31, 2025)			
Milestone 2-4 (D)	Title: Knowledge transfer and handover to basin-scale simulation and optimization studies						X	Sep 30, 2025 (Oct 31, 2025)			
Milestone 3-1 (E)	Title: Computational framework for coordinating and optimizing storage at the basin scale.					X		Mar 31, 2024 (Apr 30, 2024)			* Go/No-Go decision
Milestone 3-2 (F)	Title: Evaluation of key constraints for basin-scale capacity						X	Dec 31, 2024 (Jan 31, 2025)			
Milestone 3-3 (G)	Title: Strategies for increased storage security and capacity						X	Jun 30, 2025 (Jul 31, 2025)			
Milestone 3-4 (H)	Title: Handover of demonstrated basin-scale optimization framework to potential users						X	Sep 30, 2025 (Oct 31, 2025)			

Go/No-Go Decision Point 1: Demonstrate physics-based modeling of fault behavior at project scale

- Milestone 2-2, March 31, 2024, Project Month 18

Go/No-Go Decision Point 2: Demonstrate fast simulation of basin-scale processes for optimization

- Milestone 3-1, March 31, 2024, Project Month 18