Optimization Framework for Improved CO_2 Injectivity, Storage Permanence, Monitoring, and Utilization

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Developing the Technologies and
Infrastructure for CCS

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Presentation Outline

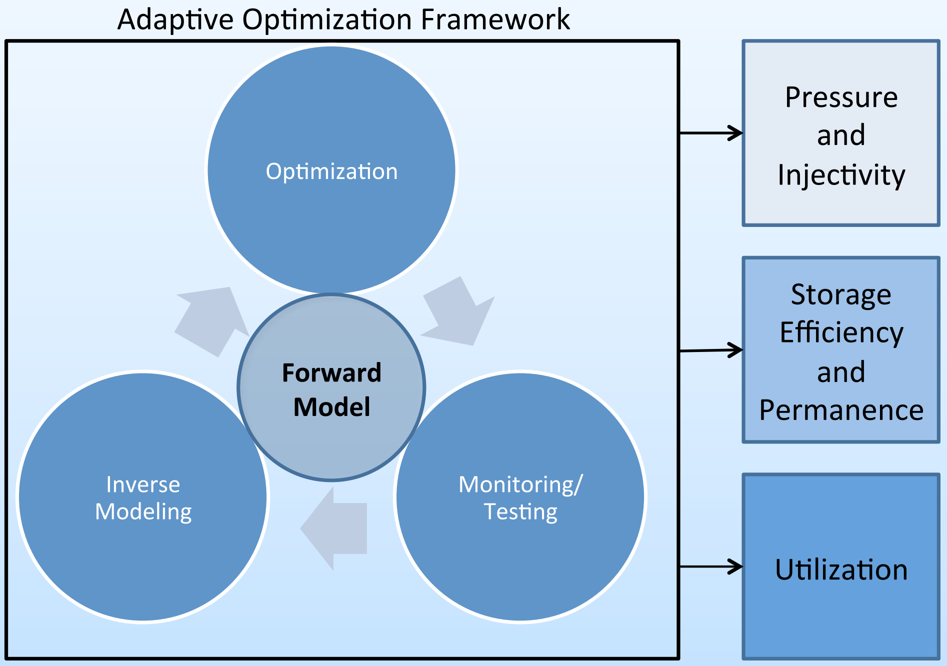
- Benefit to the Program
- Project Overview
  - **Task 1: Integrated Optimization Framework**
    The goal of this task is to develop adaptive optimization methods, and associated simulation tools, to address key challenges in CO_2 sequestration, see Tasks 2 through 5.
  - **Tasks 2 and 3: Injectivity, Storage Efficiency, and Permanence**
    The goal of these tasks is to utilize optimization methods to develop and provide new cost effective methods for improved injectivity, storage efficiency, and permanence for GCS projects
  - **Task 4: Monitoring**
    The goal of this task is to substantially improve current inversion capabilities to enable adaptive project control via monitoring, inversion, and optimization
  - **Task 5: Utilization**
    The goal of this task is to develop rigorous simulation capabilities for modeling GCS in oil reservoirs, and to use these capabilities in the optimization framework for maximum hydrocarbon recovery and maximum trapping of CO_2 (not presented today)
- Accomplishments to Date
- Project Summary

Benefit to the Program

- Tasks 1-5 provide technology that improves reservoir storage efficiency while ensuring containment
- Tasks 1-5 provide methodology that supports industry's ability to predict (or control) CO_2 storage capacity in geologic formations to within ±30 percent and develop technologies to ensure 99% storage permanence

Project Overview Task 1:
Optimization Framework and Integrated Management

- **Objectives**
  - Develop and apply an adaptive optimization framework for CO_2 storage projects which utilizes advanced automated optimization algorithms and suitable process models for coupled multi-phase behavior,
  - Use this new framework to investigate process behavior and then develop optimal schemes for key technical challenges in CO_2 sequestration,
  - Demonstrate applications for ongoing partnership or international projects and provide guidance for system optimization in future projects.

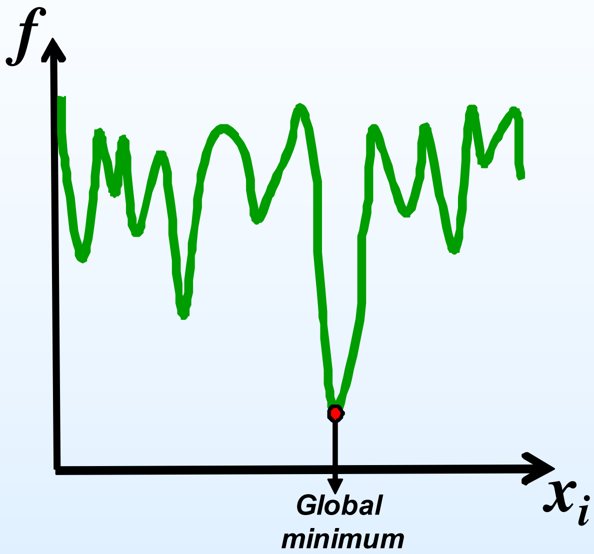


- **Technical Status**
  - Developed and demonstrated an efficient constrained global optimization methodology for realistic GCS systems
  - Currently working on development of an integrated management system for adaptive control based on dynamic model updates using monitoring data

Task 1:

Constrained Global Optimization for Optimal Control and Placement of Wells

- **Motivation**
  - Due to complex reservoir geometry and heterogeneity in reservoir properties, objective functions tend to be highly irregular with multiple local optima in the solution space
  - The irregularity of objective functions can easily cause gradient-based methods to be stuck in a local minimum



- **Objective**
  - Develop a constrained global optimization method, test for optimizing CO_2 injection and brine extraction (well placement and rates), and modify/apply to broad set of optimization scenarios

- **Approach**
  - Define specific reservoir performance criteria (e.g., maximum pressure, minimum AoR size, maximum storage efficiency, maximum trapping, minimum leakage rate)
  - Via smart optimization algorithms, automatically find most suitable CO_2 injection and brine extraction solutions that meet performance criteria and constraints
  - Optimization searches for optimum number of wells, well locations, and rates

Task 1:

Example Description of a Constrained Global Optimization Problem

A general constrained optimization problem for well placement, injection and extraction for maximum pressure control can be formally expressed as

Minimize

$$f(\boldsymbol{x}_{ext}, \boldsymbol{y}_{ext}, \boldsymbol{p}) = \frac{V_{ext}}{V_{inj}}$$

→ *Brine extraction Ratio (if no brine extraction, f is chosen as $1/V_{inj}$)*

Subject to

$$\Delta P_{th} - \max\left\{\Delta P\left(\boldsymbol{x}_f, \boldsymbol{y}_f, t\right)\right\} > 0$$

→ *Pressure buildup constraints, e.g. max buildup along a fault*

$$V_{ext,CO_2} = 0$$

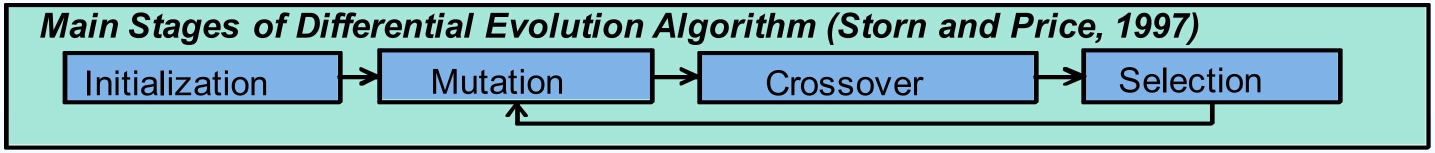
→ *No CO_2 flow into extraction wells (for brine extraction schemes)*

$$a_1 \le x_{inj,i} \le b_1,\ a_2 \le y_{inj,i} \le b_2$$

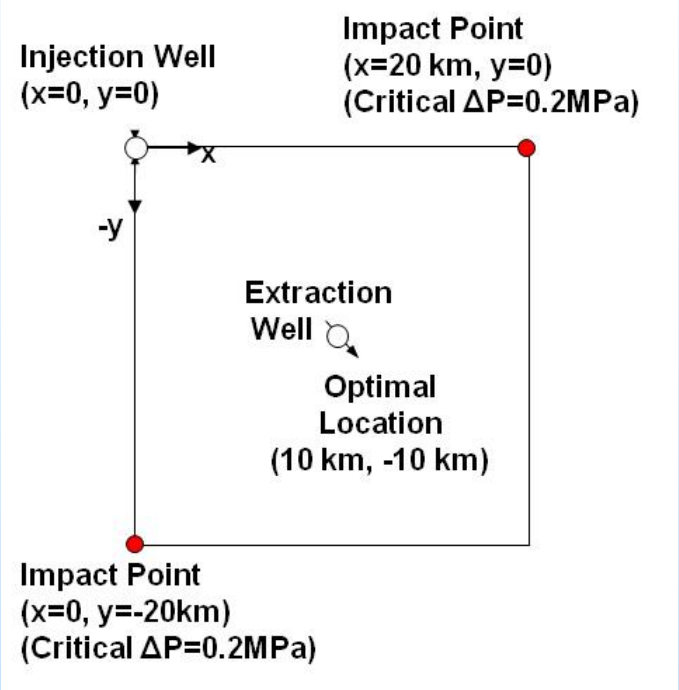
$$a_4 \le x_{ext,j} \le b_4,\ a_5 \le y_{ext,j} \le b_5$$

→ *Range of Cartesian coordinates for vertical wells (for partially penetrating and horizontal wells, additional parameters can be included)*

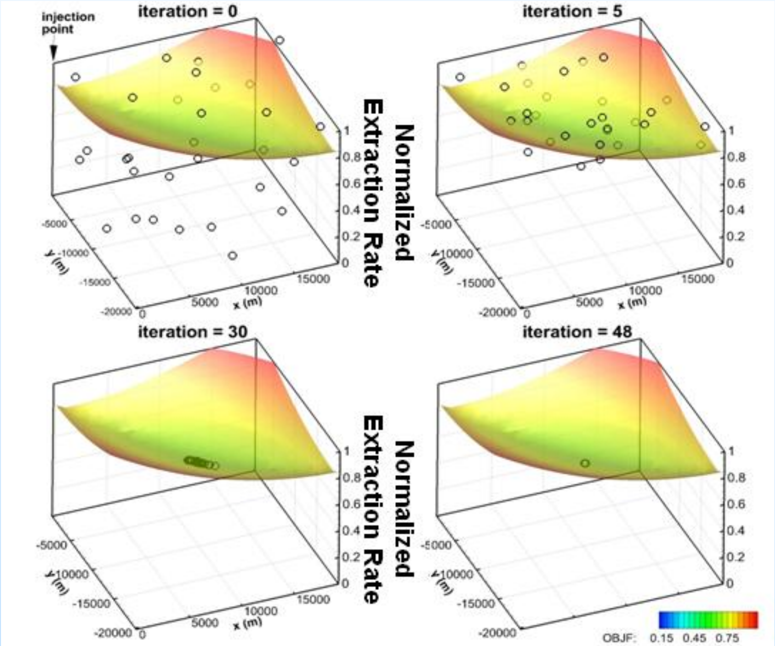
Task 1:
Constrained Differential Evolution Algorithm



A Simple Optimization Problem for Demonstration

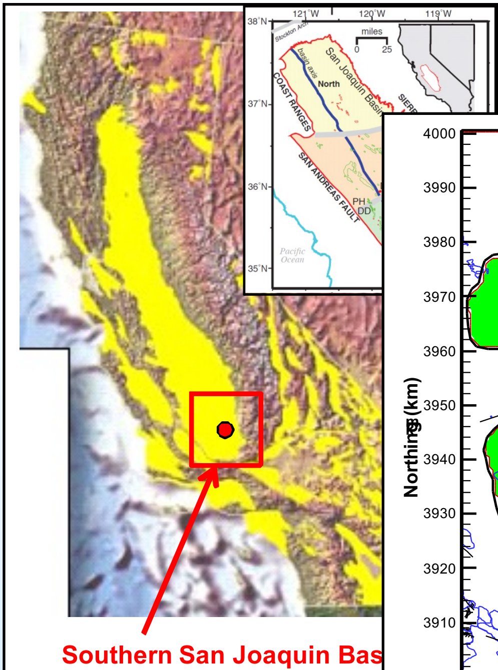


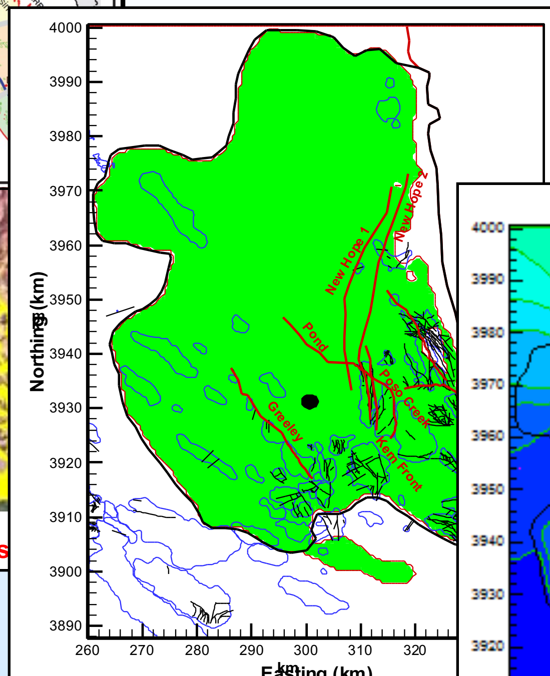
Evolution of the CDE solutions (the zones below the isosurface line are infeasible)

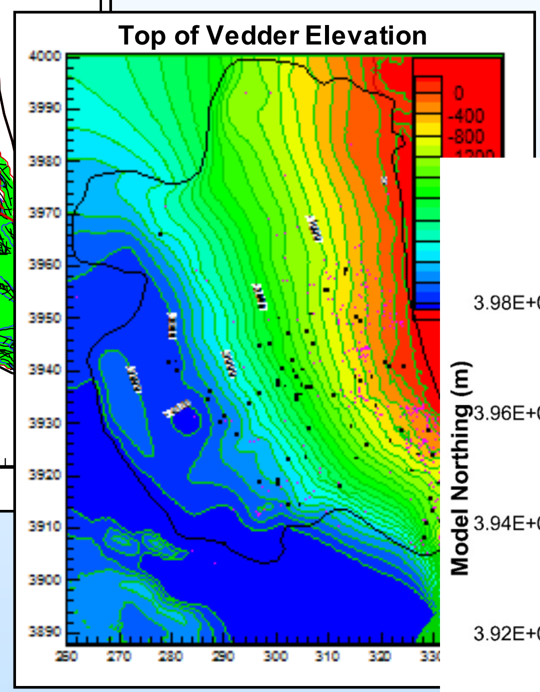


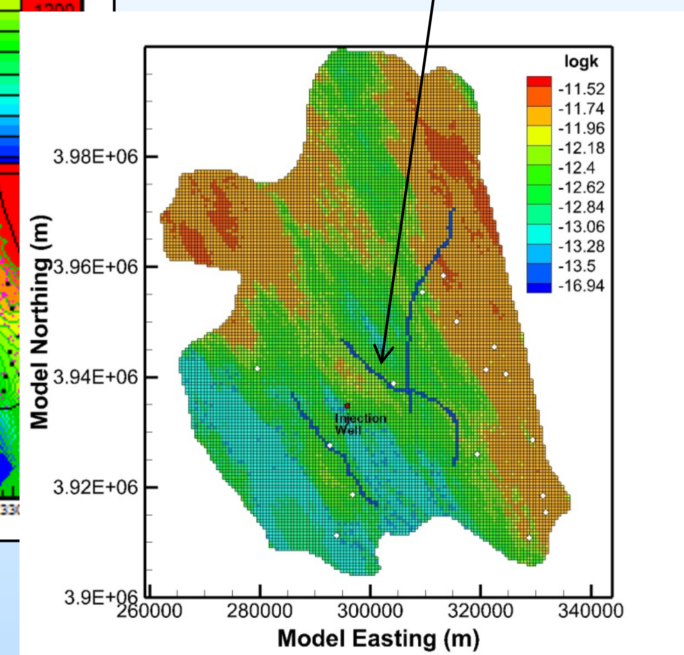
Task 1:

Application to Hypothetical CO_2 Injection in the Vedder Formation (Southern San Joaquin Valley, California)









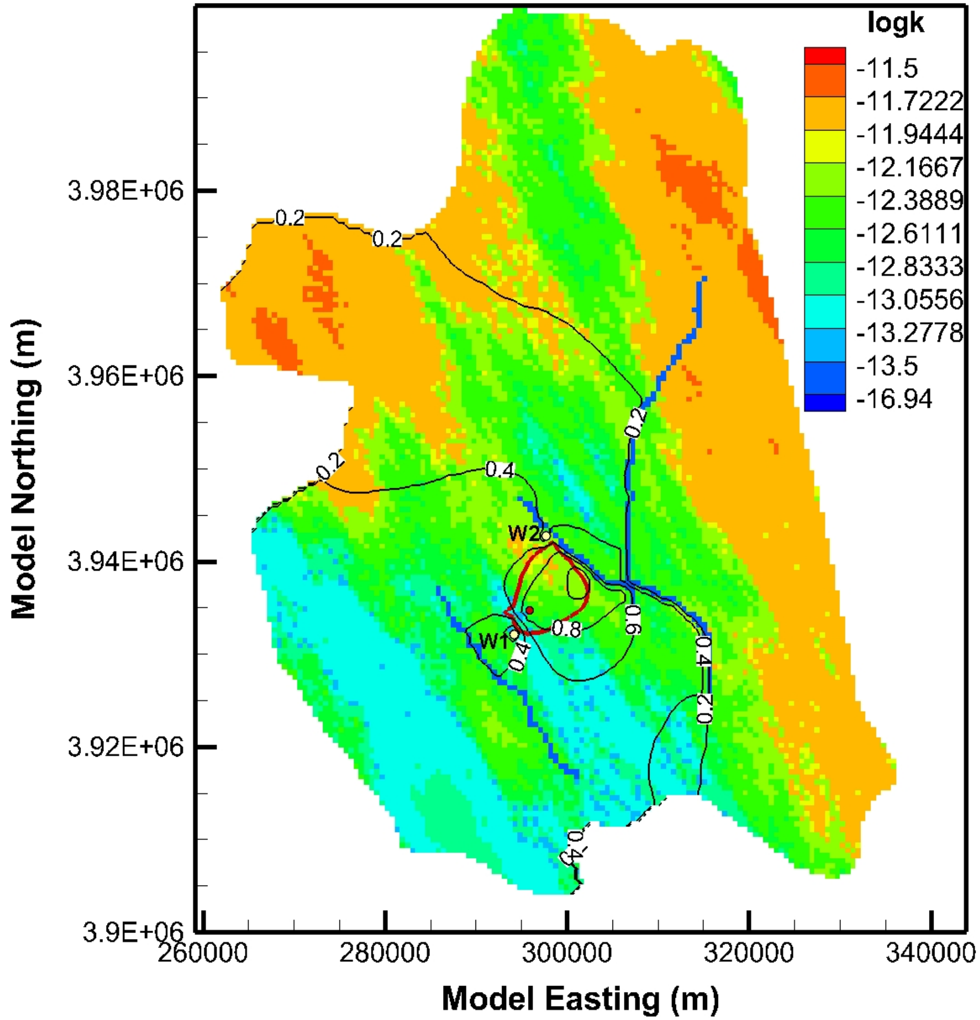
Major faults not to experience pressure buildup above 1 MPa

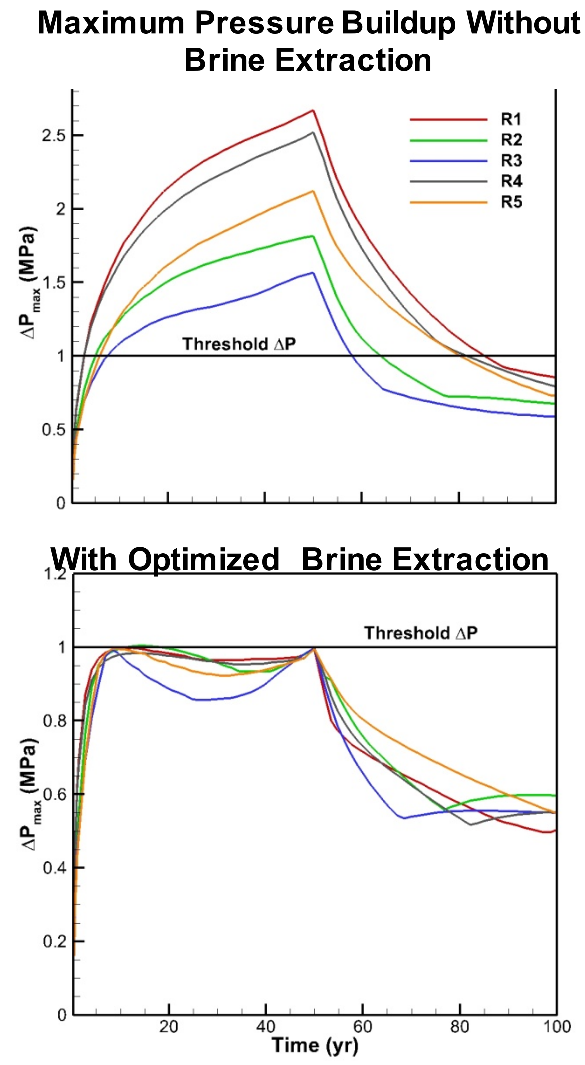
Injection Target: 5 Mt CO_2 per Year Over 50 Years

Task 1:

Optimal Well Placement and Pressure-Buildup Changes

Results for Realization 1

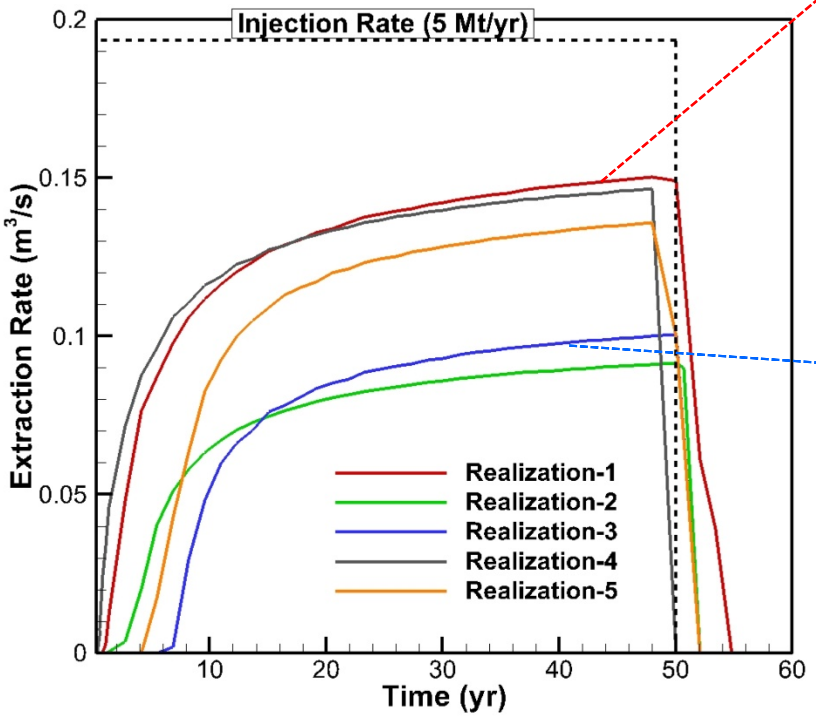


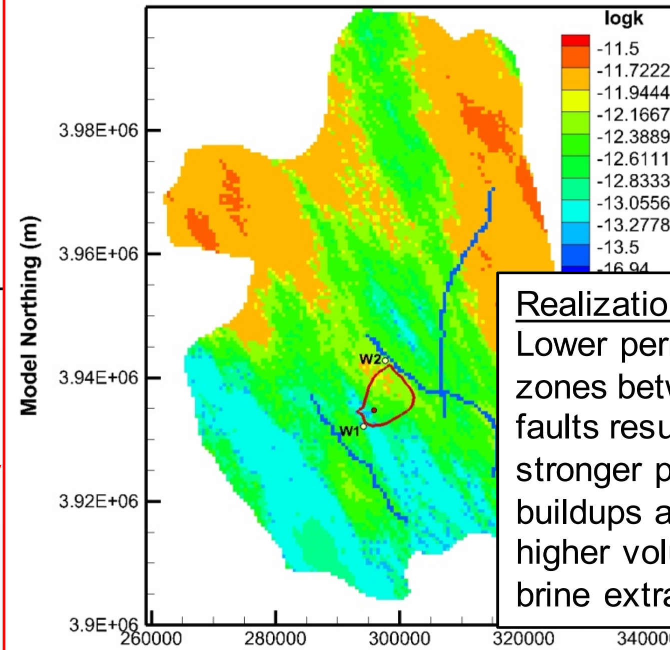


Task 1:

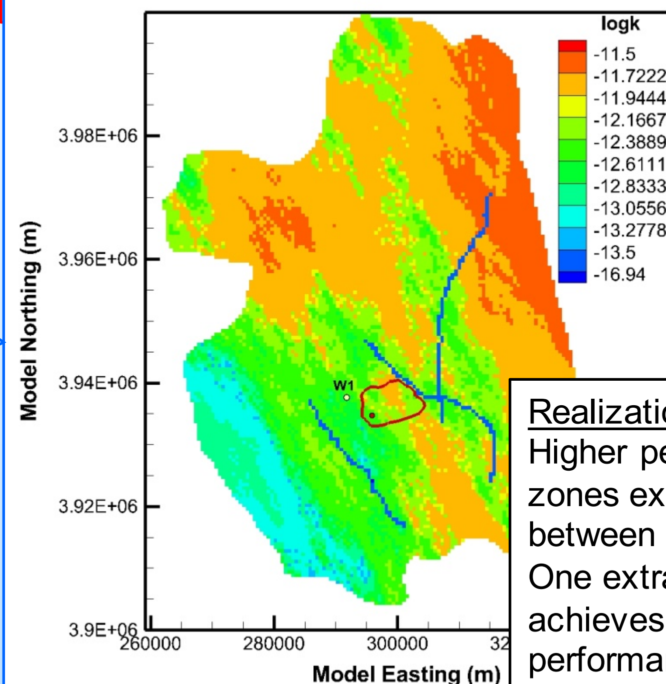
Heterogeneity plays a significant role for optimal well placement and extraction rate

R	Optimal Injection Rates without Brine Extraction for ΔP_{max}=1MPa along the Faults	Optimal Extraction Ratios for 5Mt/year injection and ΔP_{max}=1MPa along the Faults
1	1.968 Mt/yr	0.672
2	2.739 Mt/yr	0.393
3	3.229 Mt/yr	0.380
4	2.061 Mt/yr	0.654
5	2.451 Mt/yr	0.538



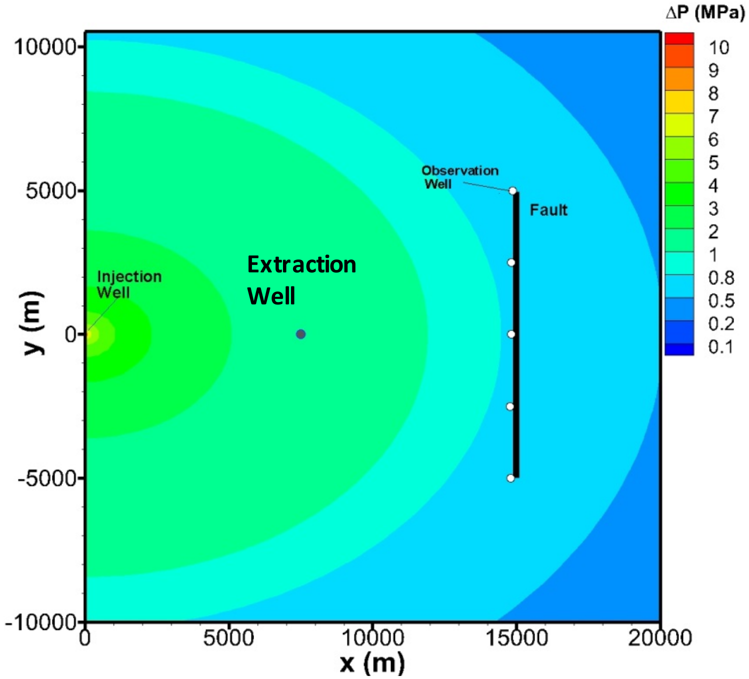


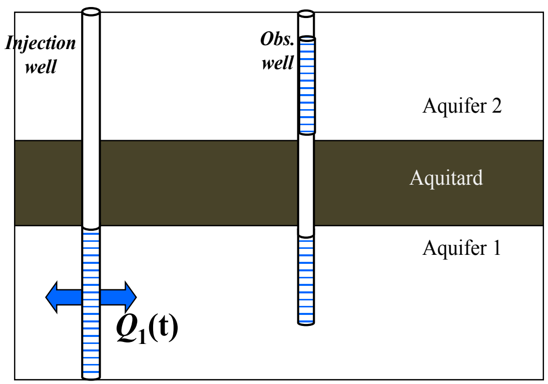
Realization-1
Lower permeability zones between the faults result in stronger pressure buildups and thus higher volume of brine extraction



Realization-3
Higher permeability zones exist between the faults. One extraction well achieves the performance goal

Task 1: An Example Application of Adaptive Approach to Project Control and Optimization

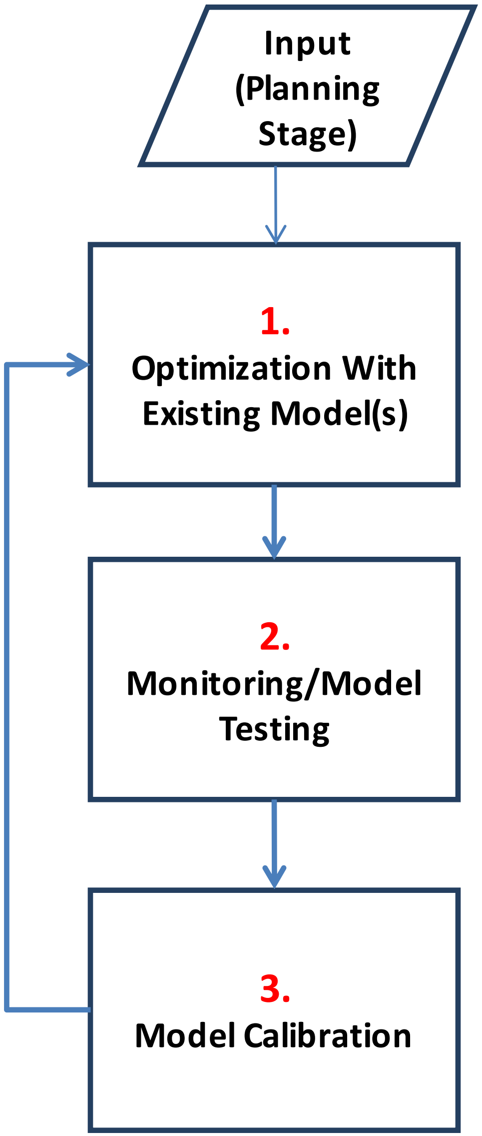


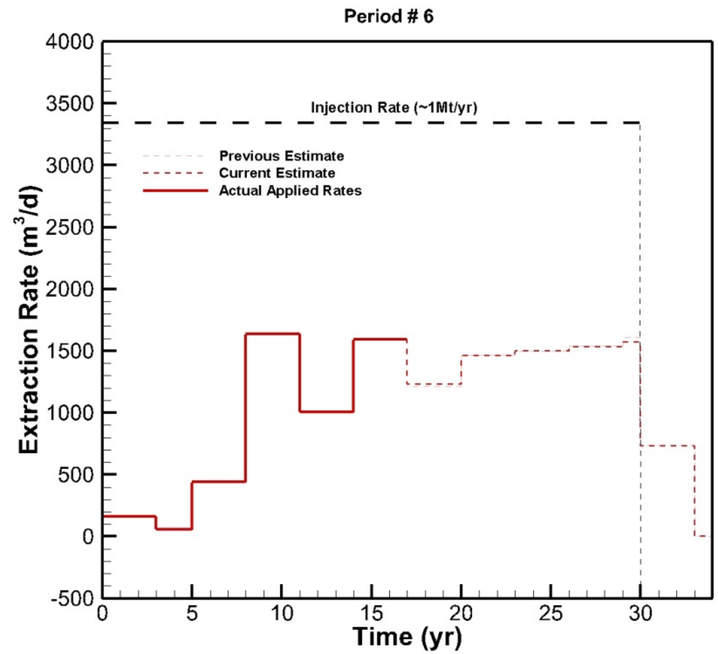


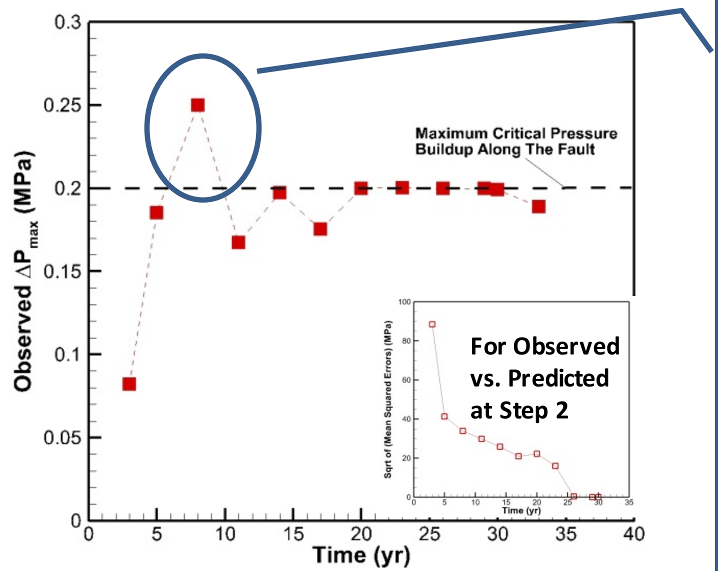
Parameters assumed to be Unknown	Actual Values
K1 (m/d)	1.015E-01
S1 (Specific Storage Coef, 1/m)	1.693E-06
Horizontal Anisotropy Ratio	2.000E+00
K2 (m/d)	1.037E-01
S2 (1/m)	1.704E-06
K' (aquitard)	1.028E-06
S' (aquitard)	1.988E-06

Objective:

- Critical pressure buildup is assumed to be 0.2 MPa along the fault
- Fluid injection rate is 1Mt/yr over 30 yrs
- A adaptive optimization algorithm involving optimization +monitoring + model update is applied to manage the system, minimizing extraction rates while attempting to reduce risk of fault slippage.







High pressure in violation of constraint indicates:

- Importance of site characterization at the planning stage
- Monitoring and model update need to be done at a higher temporal frequency at earlier times to detect higher pressures and change extraction rates accordingly

Project Overview Tasks 2 and 3:

Injectivity, Storage Efficiency, and Permanence

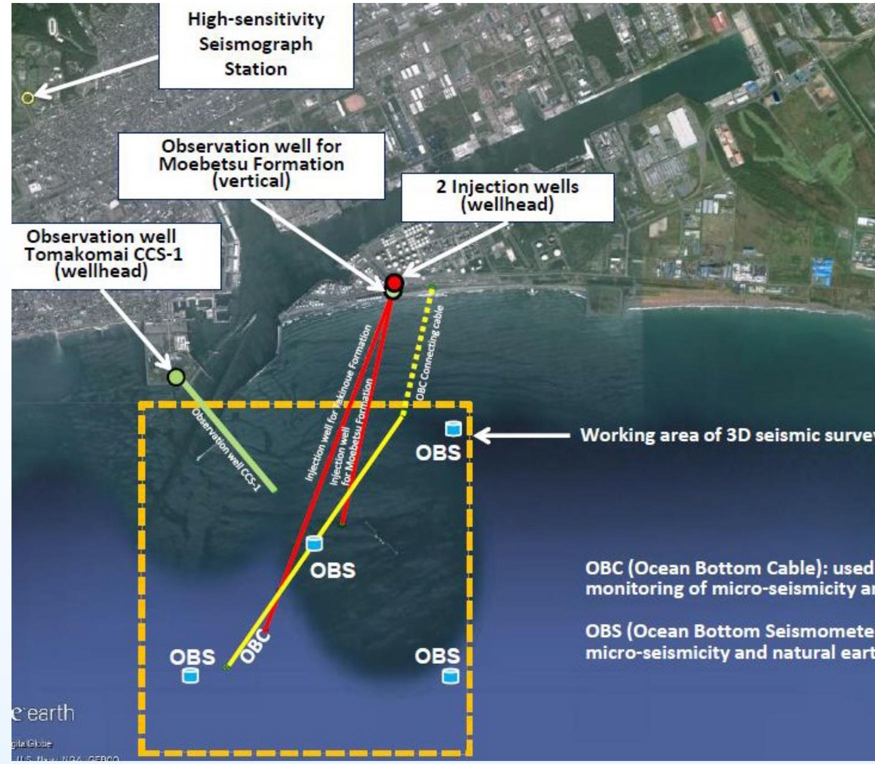
- **Objectives**
  - Investigate and optimize options of ensuring and improving injectivity, including well placement, number and design, novel adaptive injection schemes, combined CO_2 injection and brine extraction, as well as localized stimulation to be able to inject target amount of CO_2 into reservoirs with natural heterogeneity and moderate permeability,
  - Investigate and optimize injection/extraction schemes utilizing trapping mechanisms and natural heterogeneity for enhanced sweep efficiency and residual trapping of CO_2
  - Apply adaptive injection/extraction control methods based on continuously collected field data for improving storage and developing mitigation plans
  - Demonstrate the developed methods for suitable field sites/partners.

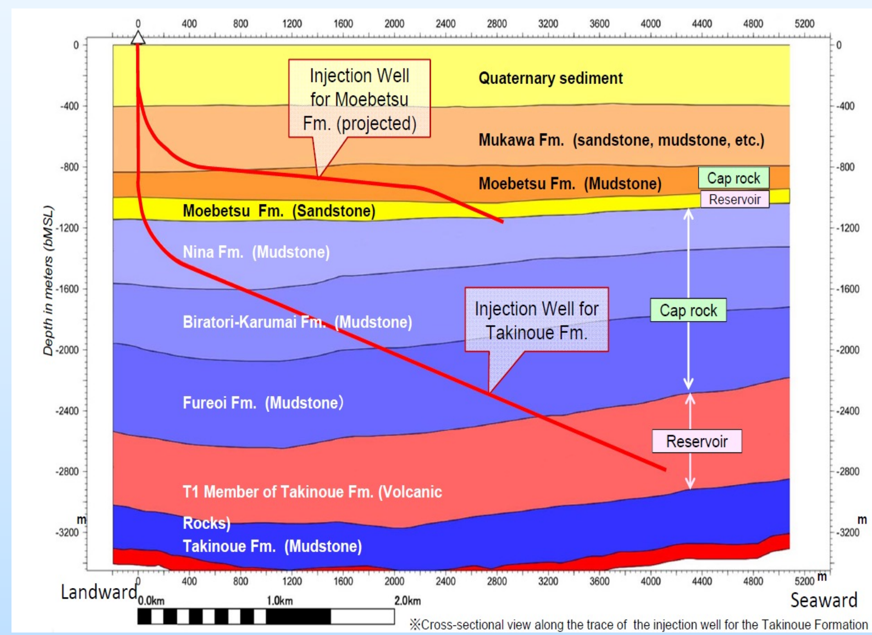
- **Technical Status**
  - Expanded the application of the CDE optimization framework for improved injectivity studies and tested for generic case studies.
  - Developed new modeling capabilities for efficiently simulating hysteresis in two-phase flow and started investigating optimal control methods for enhanced storage, trapping and plume stability
  - Selected Japanese CO_2 pilot field test at Tomakomai for demonstration of CDE-based optimization tools and initiated partnership with the Research Institute of Innovative Technology for the Earth (RITE) in Japan.

Tasks 2 and 3:

Field Demonstration of the Optimization Methods and Tools

- Tomakomai CCS demonstration project is planned to start at the beginning of 2016.
- Initially, the $scCO_2$ injection is planned for 3 years at a rate of 100Kt/yr. However, LBNL and RITE will investigate for future larger injection rates and durations using our optimization methods.
- The scCO2 will be injected into two storage layers
  - The upper injection zone - sandstone layers of Moebetsu Formation, about 1000-1200 m depth below the seabed. Porosity ~ 0.2-0.4 and permeability ~ 9-25mD.
  - The lower injection zone - volcanic and volcaniclastic rocks, about 600m thick and at 2400-3000m below the seabed. Porosity ~ 0.03-0.19 and permeability~ 0.01mD-2.6mD.
- The injection site is located nearby faults and the lower injection zone is known to have a very low permeability,
- Concerns about possible injection-induced seismic effects and low injectivity require reservoir pressure management methods for optimal control of the injection operation and brine extraction. Optimization studies will be conducted by LBNL.



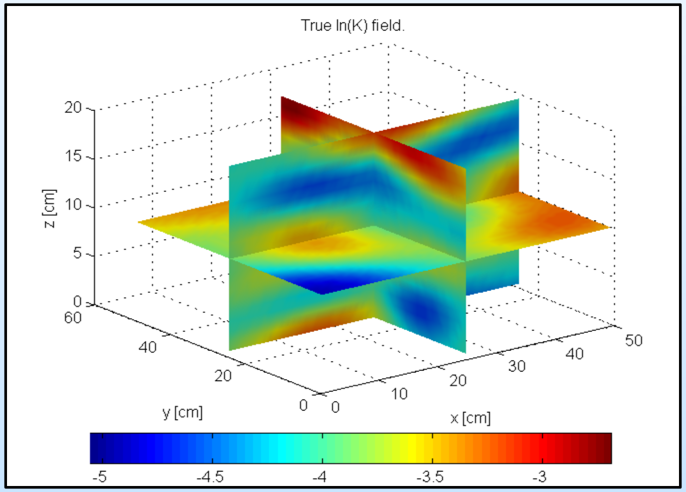


Project Overview Task 4:

Monitoring and Inverse Modeling

- **Objectives**
  - Develop intelligent data analysis and inversion approaches that allow for fast interpretation and analysis
  - As a first step, implement advanced stochastic inversion toolset into optimization framework and demonstrate applicability of toolset in real storage conditions
  - Long-term goal is to enable adaptive project control involving monitoring, analysis, efficient joint inversion, and optimization

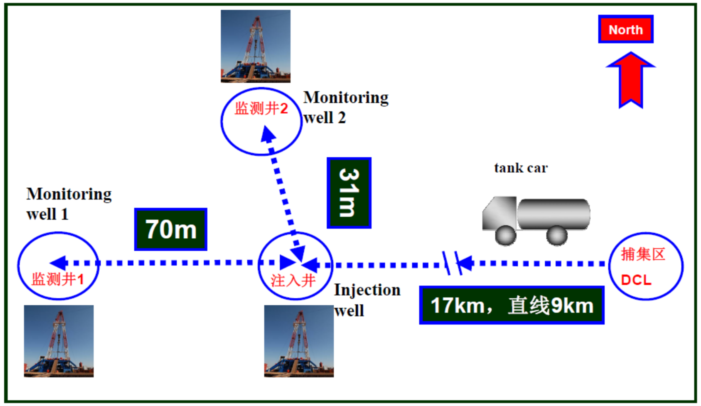
- **Technical Status**
  - Tested different stochastic inversion tools and demonstrated use for Ketzin Project (Liu et al., 2013, 2014); implementation into the optimization framework is ongoing
  - Completed data collection and analysis for the Shenhua Ordos CCS Project in China
  - Currently conducting different types of inverse modeling to demonstrate applicability and use of inverse modeling tools to the Shenhua Project



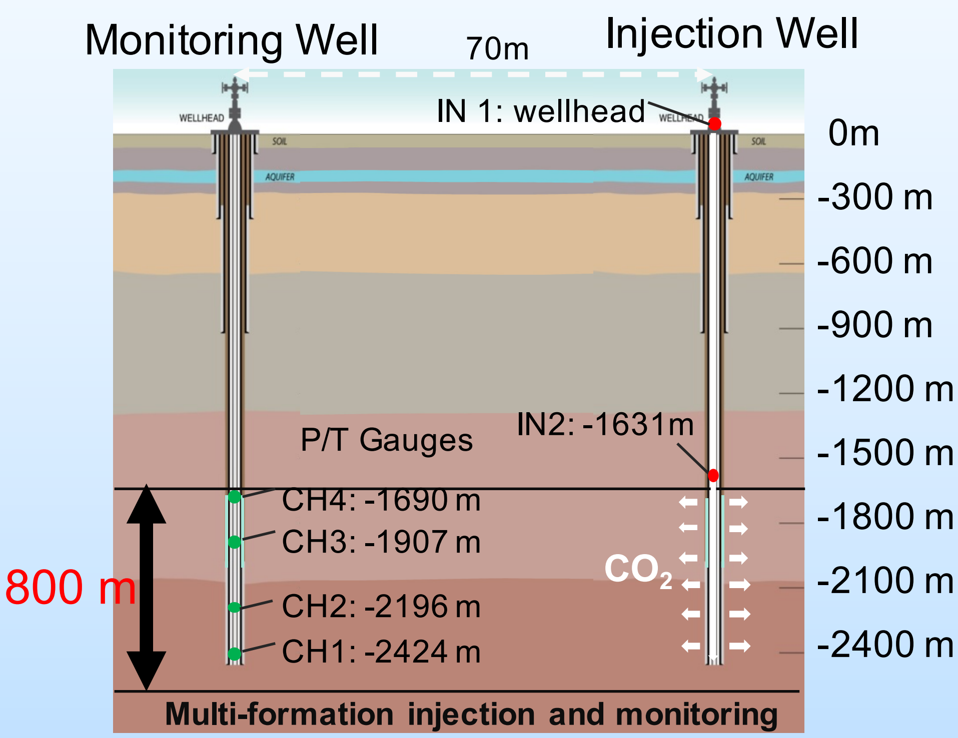
Task 4:

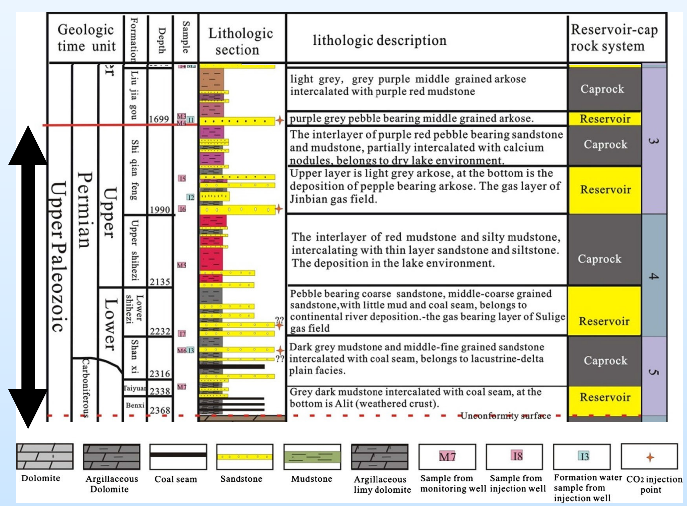
China's Shenhua Ordos CCS Project: Site Description

- Four main low-permeability storage units (< 5 md), with multiple layers, ranging in depth between 1680 m and 2520 m;
- Injection well perforated in 18 layers, with a total thickness of 88 m over the 800 m thick sandstone/mudstone sequence.



One injection well and two monitoring wells and CO_2 source from a DCL plant



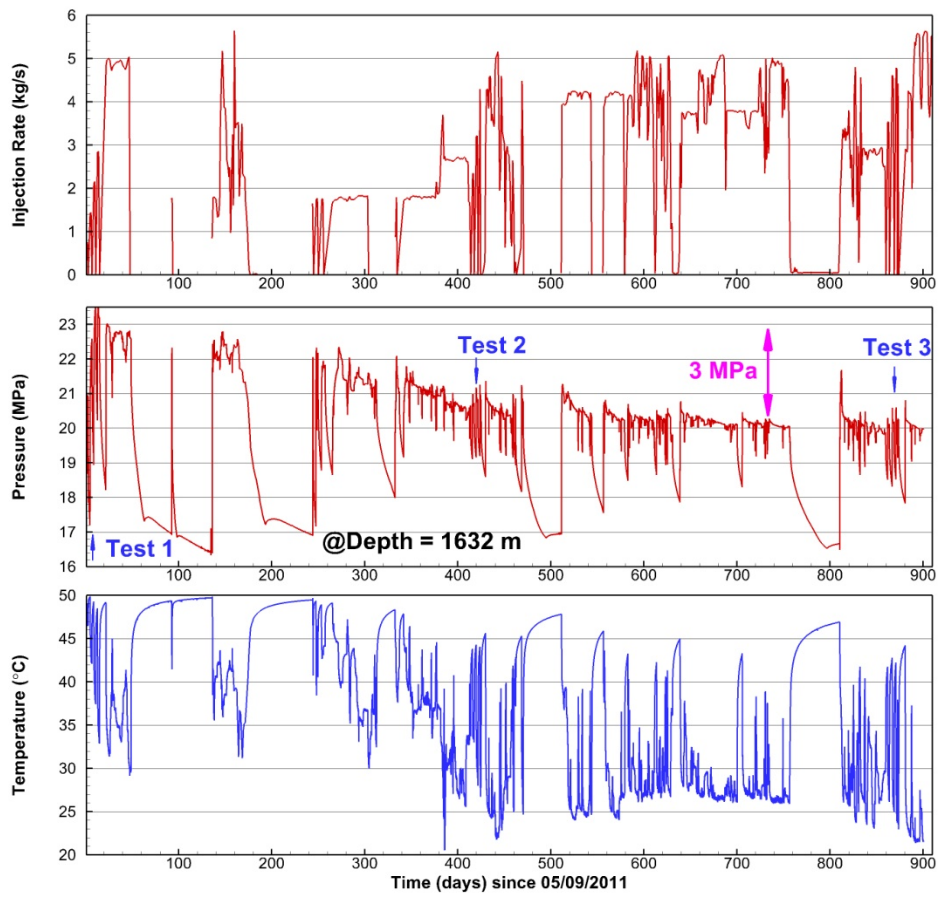


Storage complex: multiple layers for injection (88 m) and storage (800 m)

Task 4:

CO_2 Injection: Unique Features

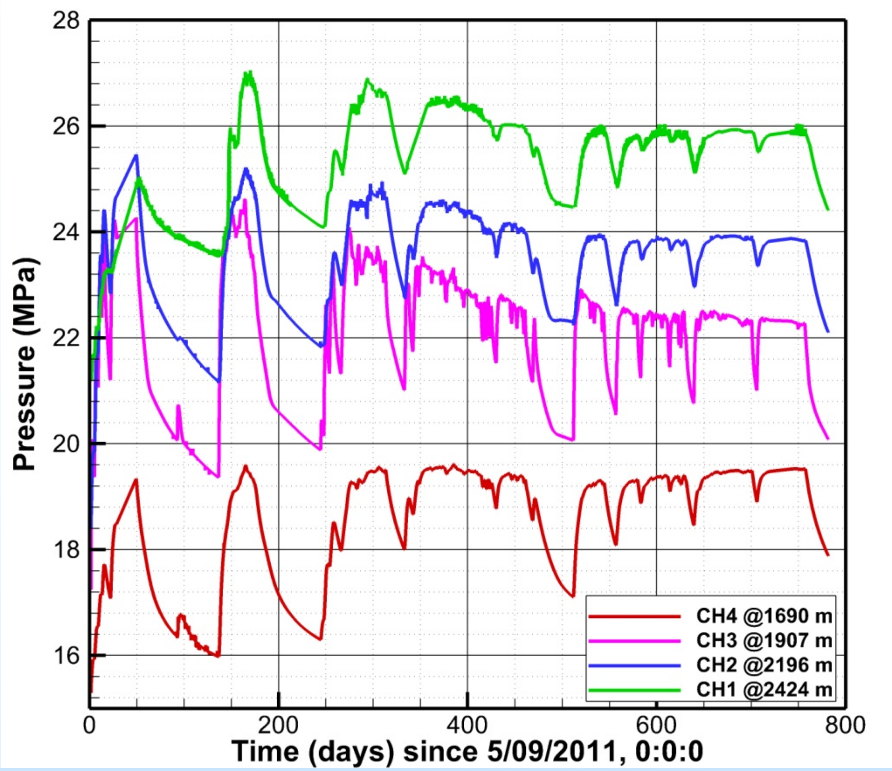
- Injection of liquid CO_2 at 0 °C or less at ~0.1 Mt/year, with cumulative injected CO_2 mass of 0.280 Mt from May 2011 to August 2014
- Bottomhole injection pressure decreases with time by more than 30 bar, indicating significantly enhanced injectivity;
- Bottomhole temperature decreases by 30 °C under injection conditions;
- Three step-rate injection/shut-in tests were conducted, once each year, to characterize the dynamics of the storage system.



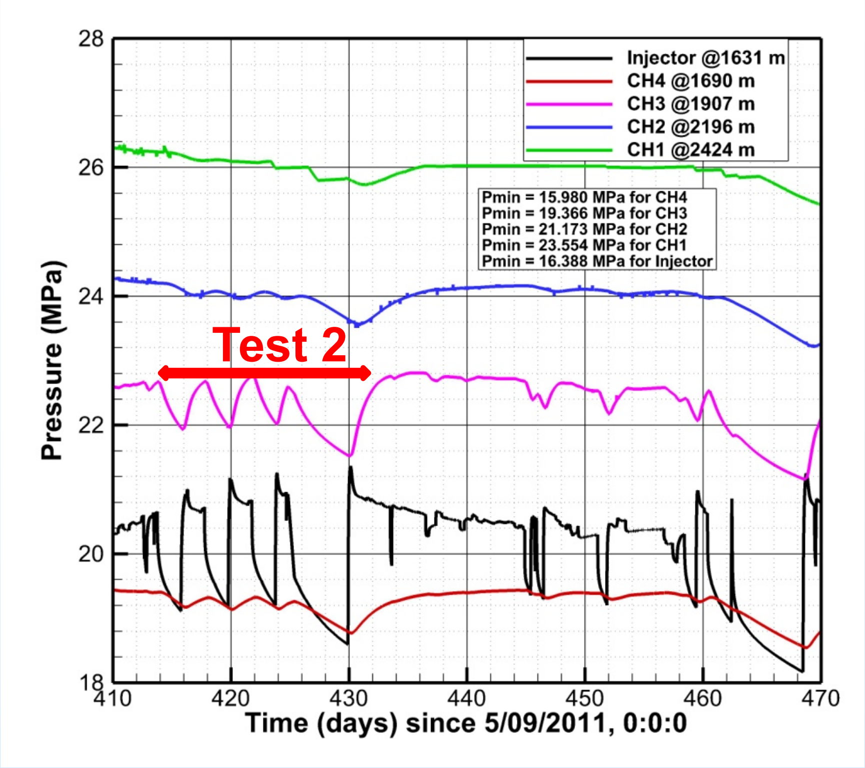
Bottomhole (@1631 m) pressure and temperature at the injection well (data shared from Beijing Normal University, China)

Task 4:
Multi-formation Pressure Monitoring: Operation and Tests

- Multi-formation pressure monitoring during injection operation and step-rate injection/shut-in tests provides useful information
- Inverse modeling is under way to (1) estimate formation permeability and dynamics of two-phase flow, and (2) explore causes of enhanced injectivity



Multi-formation pressure responses during injection operation at the monitoring well 70 m from the injector



Multi-formation pressure responses to injection pressure (black) during the 2nd test

Accomplishments to Date

- Task 1: Integrated Optimization Framework
  - Developed a new constrained global optimization method involving injection/extraction well placement and rates, and applied the global optimization methodology to realistic complex problems involving pressure control near faults and other management objectives (e.g., improved injectivity and storage)
  - Adaptive optimization capabilities for integrated optimization framework currently under development
- Tasks 2 and 3: Injectivity, Storage Efficiency, and Permanence
  - Expanded the application of the optimization method for improved injectivity and tested its applicability successfully for generic case studies
  - Developed new modeling capabilities for efficiently simulating hysteresis in two-phase flow to investigate optimal control methods for enhanced storage, trapping and plume stability
  - Identified Japanese CO_2 pilot field test at Tomakomai for demonstration of CDE optimization tools and initiated partnership with RITE in Japan
- Task 4: Monitoring and Inverse Modeling
  - Implemented and tested different stochastic inversion tools into the unified optimization framework
  - Completed data collection and analysis for the Shenhua Ordos Project

Summary

- **Key Findings / Lessons Learned from Modeling Tasks**
  - The constrained differential evolution algorithm is very well suited for solving complex and challenging storage management optimization problems
  - Heterogeneity plays a significant role for optimal well placement and injection/extraction rate control, which points to the importance of site characterization and use of adaptive management strategies combining monitoring+inversion+optimization in an integrated framework
  - Advanced stochastic inversion algorithms have notable potential for joint analysis of large data sets and will be useful for adaptive optimization frameworks
- **Future Plans**
  - Long-term plan is to develop and demonstrate a broad and flexible GCS optimization framework for improved injectivity, storage efficiency and permanence, monitoring, and utilization for ongoing or planned real project sites
  - This planned work builds on developments made in recent years, such as the advanced global and local search algorithms for pressure management, and the advanced stochastic joint inversion methods for fast and intelligent analyses/processing of field data
  - The optimization framework, including constrained global and local optimization methods, will allow for adaptive control, in the sense that storage management decisions can be revised from time to time using feedback from monitoring data

Appendix

– These slides will not be discussed during the presentation, but are mandatory

Appendix: Organization Chart

- "Optimization Framework for Improved CO_2 Injectivity, Storage Permanence, Monitoring, and Utilization" is a subtask of LBNL's Core Carbon Storage and Monitoring Research program
- "Optimization Framework" has five main tasks with principal investigators identified as PI
  - Task 1: Jens Birkholzer (PI), Abdullah Cihan, Stefan Finsterle
  - Task 2: Abdullah Cihan (PI)
  - Task 3: Abdullah Cihan (PI)
  - Task 4: Quanlin Zhou (PI), Xiaoli Liu
  - Task 5: Curtis Oldenburg (PI) and Lehua Pan
- List of scientific staff

Name	Title	Role in Task/Subtask
Jens Birkholzer	PI and Senior Scientist	Lead scientist for Modeling CO_2 Processes
Abdullah Cihan	PI and Research Scientist	Lead scientist working on storage management and optimization
Curtis Oldenburg	PI and Senior Scientist	Lead scientist for CO_2-EOR simulations
Quanlin Zhou	PI and Research Scientist	Lead scientist working on stochastic inversion
Xiaoyi Liu	Postdoctoral researcher	Main scientist working on stochastic inversion
Stefan Finsterle	Research Scientist	Main scientist working on integrated optimization framework
Lehua Pan	Research Scientist	Main scientist working on CO_2-EOR simulations

Appendix: Gantt Chart for FY15

Task/Milestone — Fiscal Year / Quarter	FY15			
Task/Milestone	**Q1**	**Q2**	**Q3**	**Q4**
Task 1: Integrated Optimization Framework				
Identify suitable field sites/partners		**G**		
Develop methodology for adaptive management				**H**
Task 2: Injectivity				
Develop optimization methods for improved injectivity				
Test and demonstrate methods for generic and field scenarios				
Task 3: Storage and Permanence				
Improve models for simulating hysteresis for storage and trapping optimization				
Investigate methods for injection/extraction schemes for enchanced storage				
Task 4: Monitoring and Inverse Modeling				
Implement and test advanced stochastic inversion tools				
Apply inverse modeling tools to site-specific CCS projects				
Task 5: Utilization				
Implement approaches for high-pressure solubilities of water-oil-CO_2 mixtures				
Testing of the new T2 CO2-EOR code against published results of solubility				

Appendix: Milestone Log for FY15

Task 1: Integrated Optimization Framework

– Milestone 4-1 (G), Q2 (3/31/15)
  Title: Identify suitable field sites/partners for demonstration of optimization toolset.
– Milestone 4-2 (H), Q4 (9/30/15)
  Title: Identify suitable field sites/partners for demonstration of optimization toolset.

Task 2: Injectivity

– No milestone in FY15

Task 3: Storage and Permanence

– No milestone in FY15

Task 4: Monitoring and Inverse Modeling

– No milestone in FY15

Task 5: Utilization

– No milestone in FY15

Appendix: Bibliography 2008-2015

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