Inexpensive Monitoring and Uncertainty Assessment of CO_2 Plume Migration

DOE-FE0004962

Steven Bryant and Sanjay Srinivasan

The University of Texas at Austin

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

August 20-22, 2013

Presentation Outline

- Motivation and relevance to Program
- Project goals
- Technical status
- Accomplishments
- Summary
- Future plans

Benefit to the Program

- Program goal being addressed:
  - Develop and validate technologies to ensure 99% storage permanence
- Project benefits statement:
  - The project will implement a novel computational approach for monitoring the location of CO_2 during injection. The approach has two notable advantages: it is very inexpensive, and it quantifies the uncertainty in the plume location. It thus addresses the primary objective of DOE Carbon Storage Program, *viz*. technologies to cost-effectively store and monitor CO_2 in geologic formations. One significant potential benefit will be low-cost “early warning” of unanticipated plume movement.

Project Overview (1): Goals and Objectives

- **Overall objective**: new technique for probabilistic assessment of CO_2 plume migration based on paradigm of geological model-selection using injection data

- Project goals
  - quantify connectivity/dynamic characteristics of large ensemble of geologic models
  - group models based on connectivity characteristics
  - perform model selection within Bayesian framework
  - develop modular software for implementing the technique

Program Goal Supported

Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones

Relevance to Program Goal

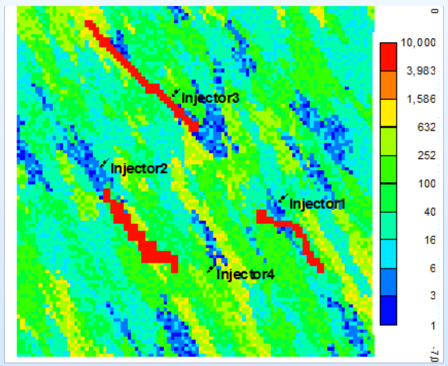
Cost-effective technique for enhanced monitoring increases likelihood of 99% containment, especially if enables proactive remediation of plume direction

Project Overview (2):
Goals and Objectives

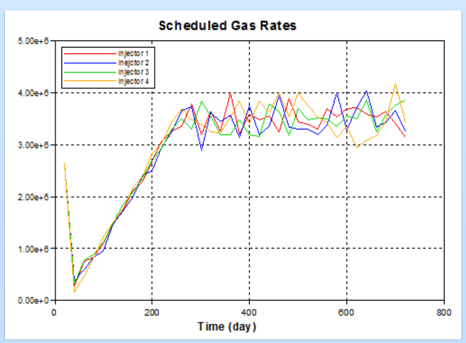
- Success criteria
  - **Decision Point 1: Q3 Y1.** *What are the limits of applicability of the proposed approach for inferring plume location from injection data alone?*
  - **Decision Point 2: End Phase 1 (Q2 Y2).** *Can we efficiently apply the new technique developed in this research to infer plume location and its uncertainty?*
  - **Decision Point 3: End Phase 2 (Q1 Y3).** *Can we deploy the modular software such that it could be integrated with existing tools and frameworks for risk assessment?*

Technical Status:
Concepts and technical basis

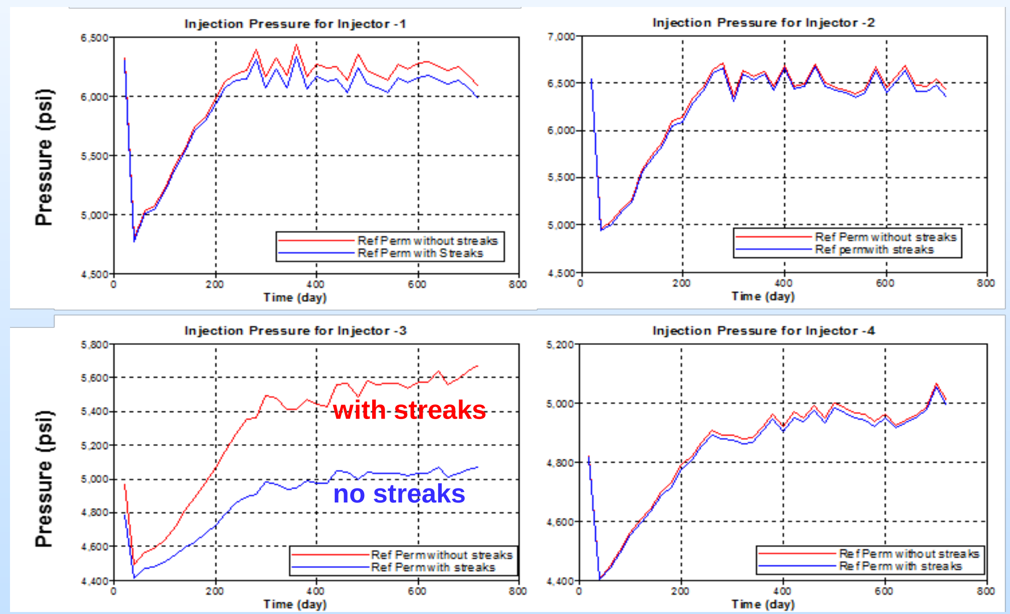
- (1) Injection data sensitive to presence of heterogeneous features (streaks, baffles) *especially when the injection rate exhibits some fluctuations*



Permeability Heterogeneity



Gas Injection Rate

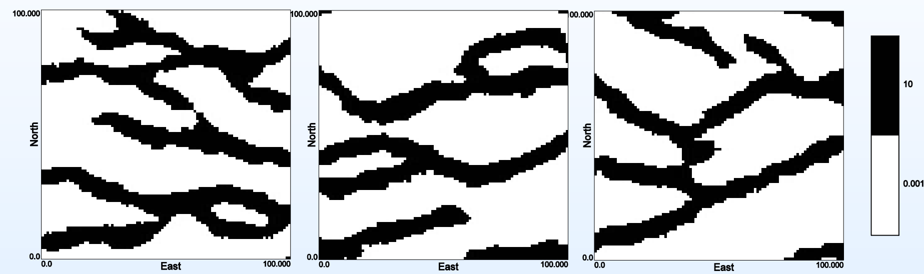


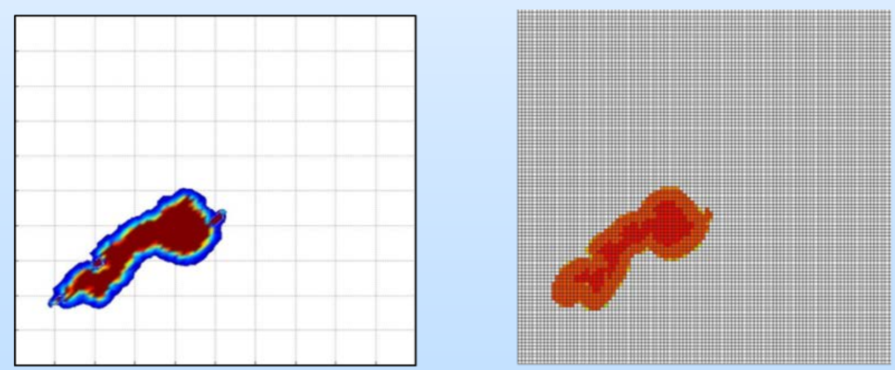
Injection Well Bottom Hole Pressures

from Mantilla et al., 2008

Technical Status:
Concepts and technical basis

- (2) Large prior uncertainty in geology
  - Inadequate characterization of aquifers
  - Has to be accounted for when deriving probabilistic estimates for plume migration
- (3) A simple, efficient proxy can capture effect of physics that control plume movement
  - Particle tracking algorithm
  - Compressibility and permeability effects captured

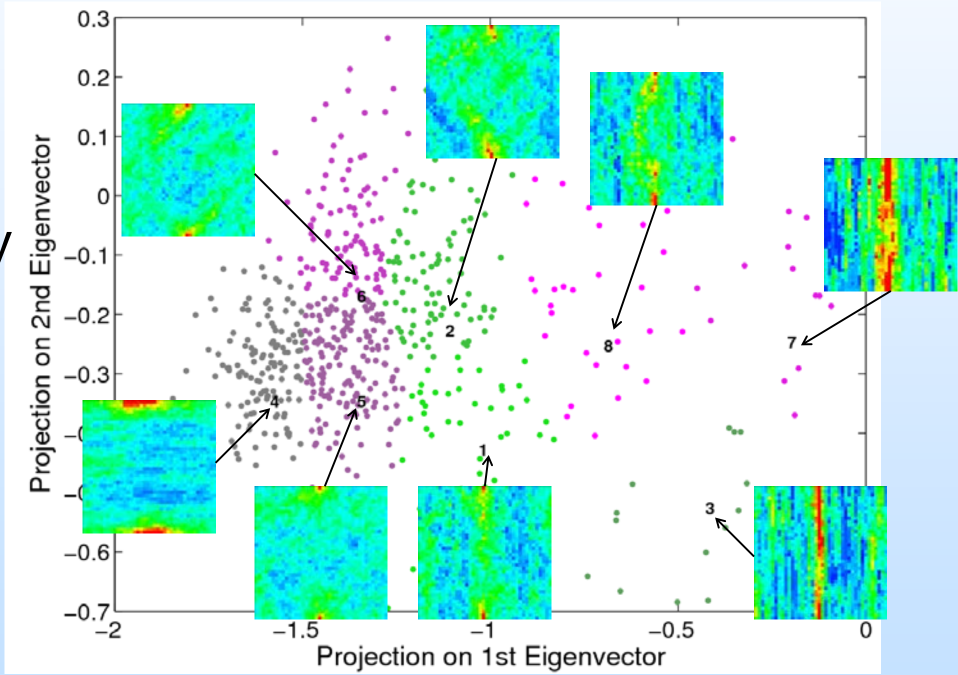




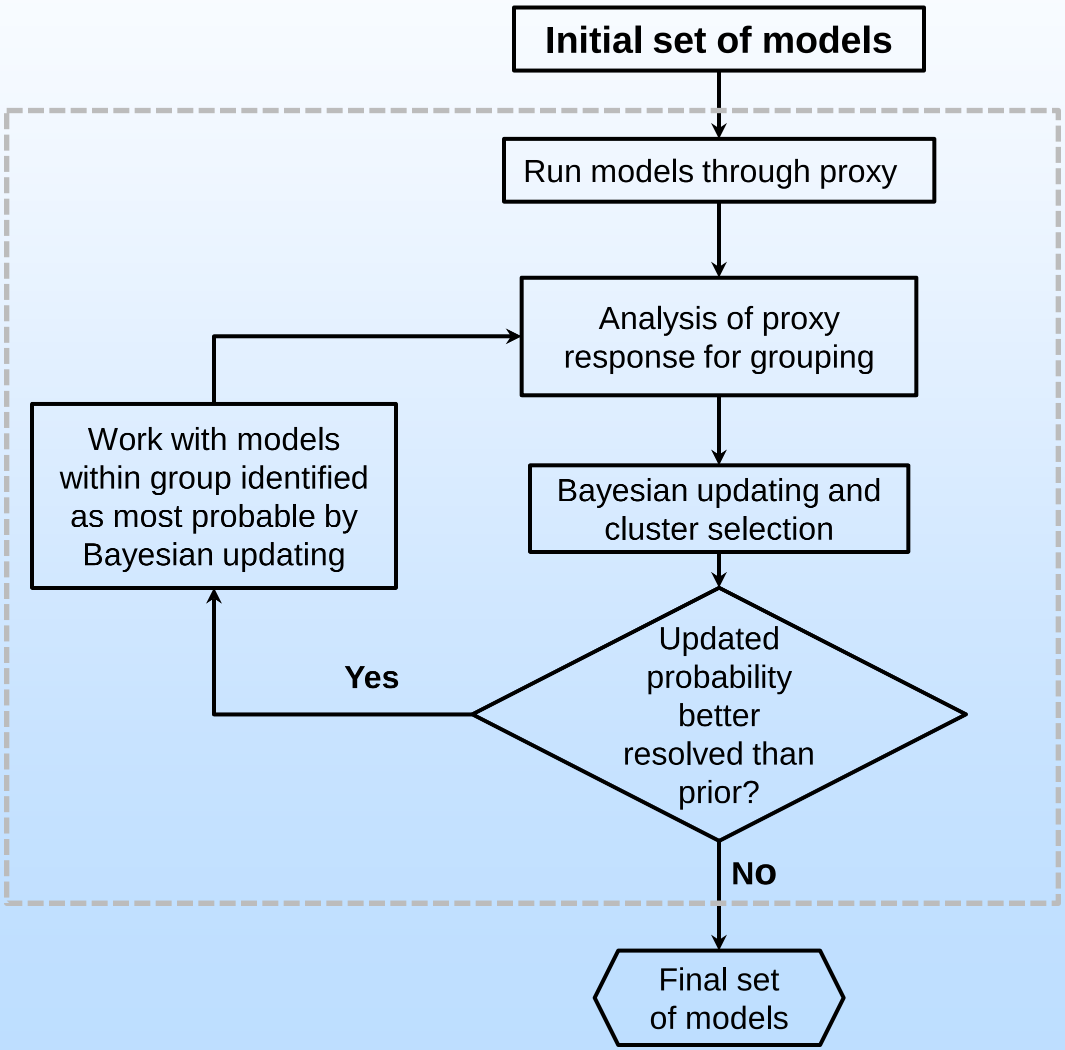
Proxy response (left) gives very similar plume shape to full-physics simulator (right)

Technical Status:
Concepts and technical basis

- (4) Multivariate classification techniques can differentiate models
  - Studied by Mantilla, 2010 for a EOR process
  - Compute distance or dissimilarity between models from proxy response
  - Perform principal component analysis of distance matrix
  - Group models using cluster analysis of principal components
- Models exhibit an orderly transition in the eigen-space

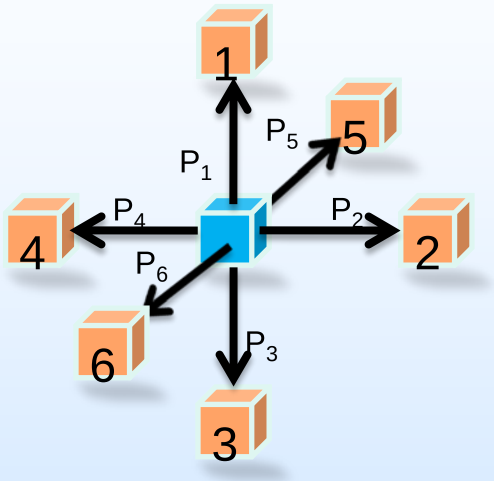


Technical Status:
Concepts and technical basis



Technical Status:

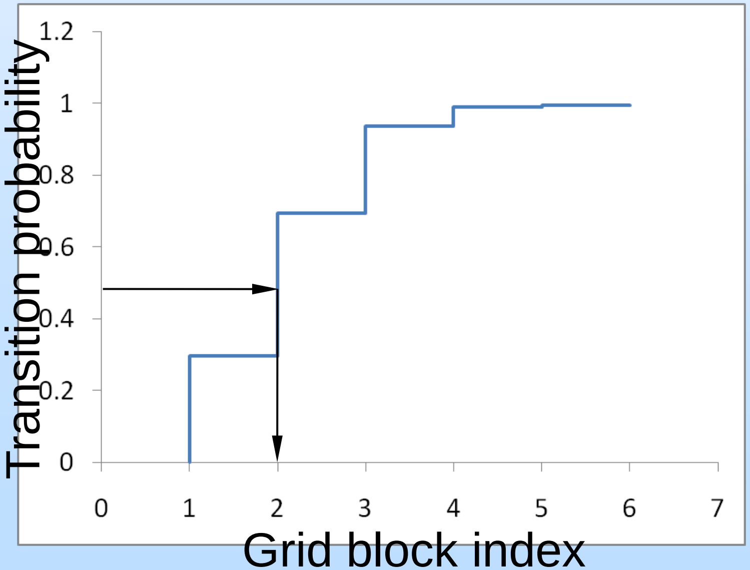
Fast transfer function and validation cases

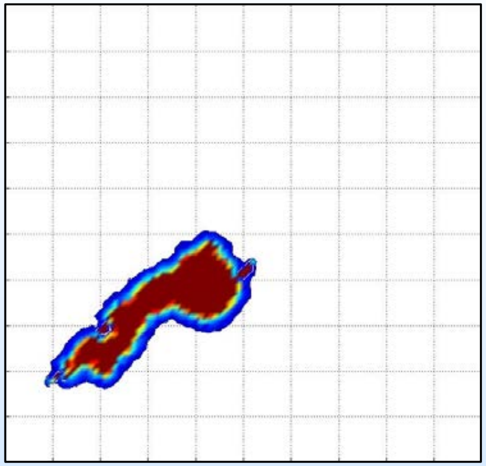


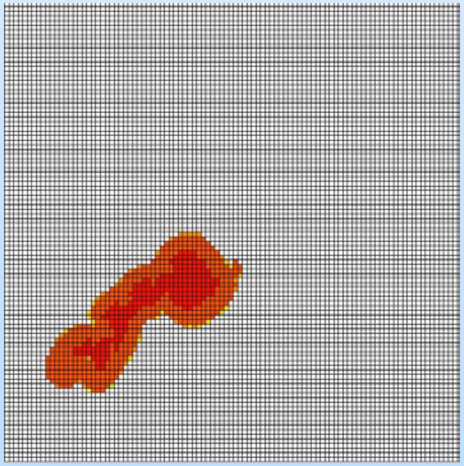
Particle Tracking Algorithm (**Sayantan Bhowmik**)

Transition probability depends on:

- Permeability
- Local pressure gradient
- Number of particles already present in target block
- Difference in particle count between current and target blocks



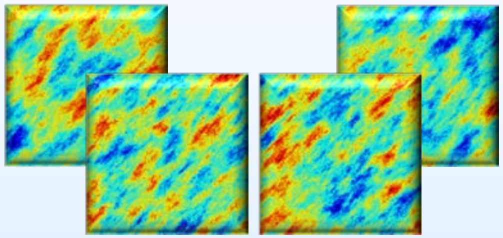




Technical Status:

Optimized Proxy Measurement Locations

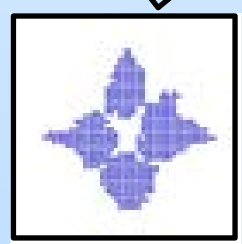
Rather than using pre-determined locations, infer locations based on maximizing dissimilarity of proxy response



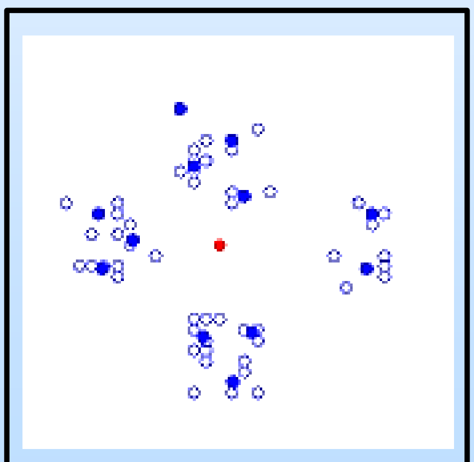
PROXY

Particle Density at all locations for all models

Covariance/similarity between particle density at different locations



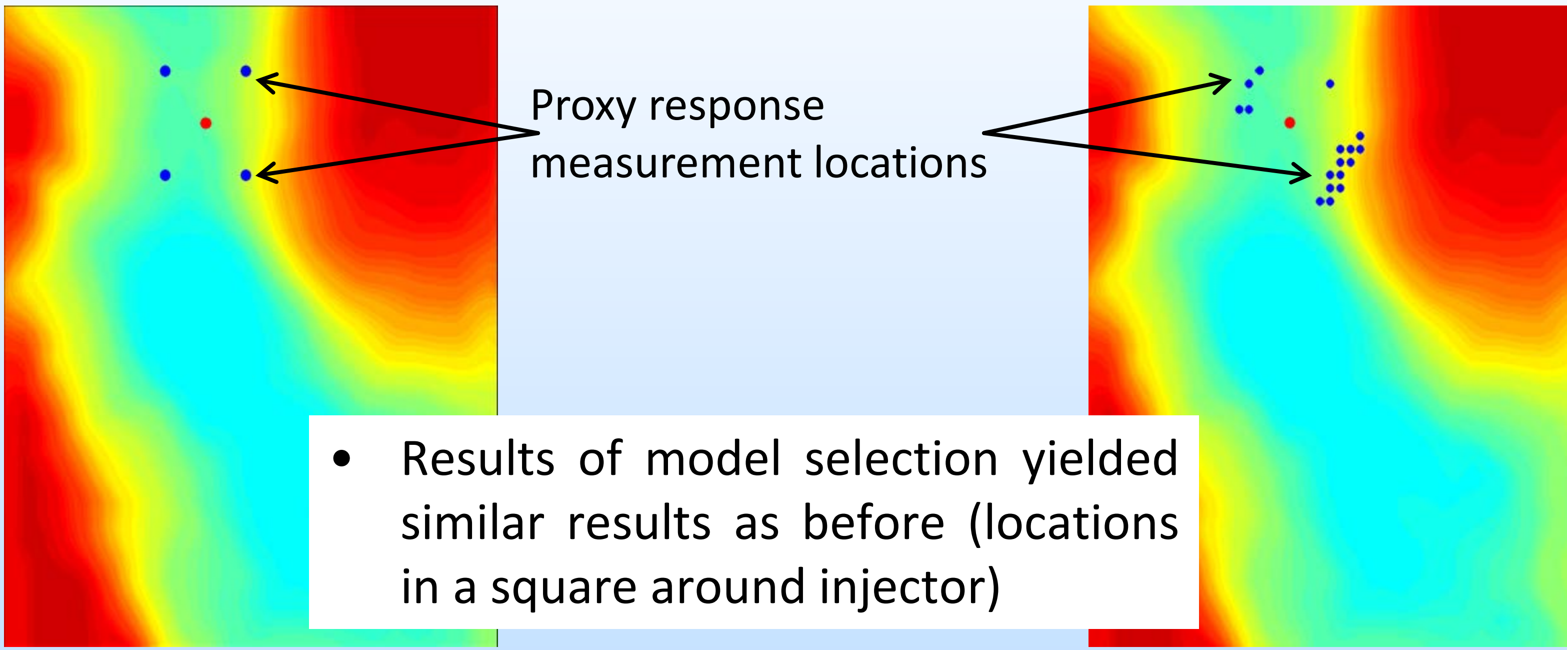
PRINCIPAL COMPONENT ANALYSIS



Locations for monitoring proxy response(s)

Technical Status:
Optimized Proxy Measurement Locations

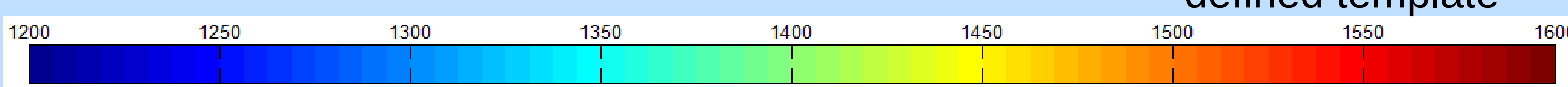
monitoring locations using new method for Krechba



- Results of model selection yielded similar results as before (locations in a square around injector)

Monitoring locations on a square template

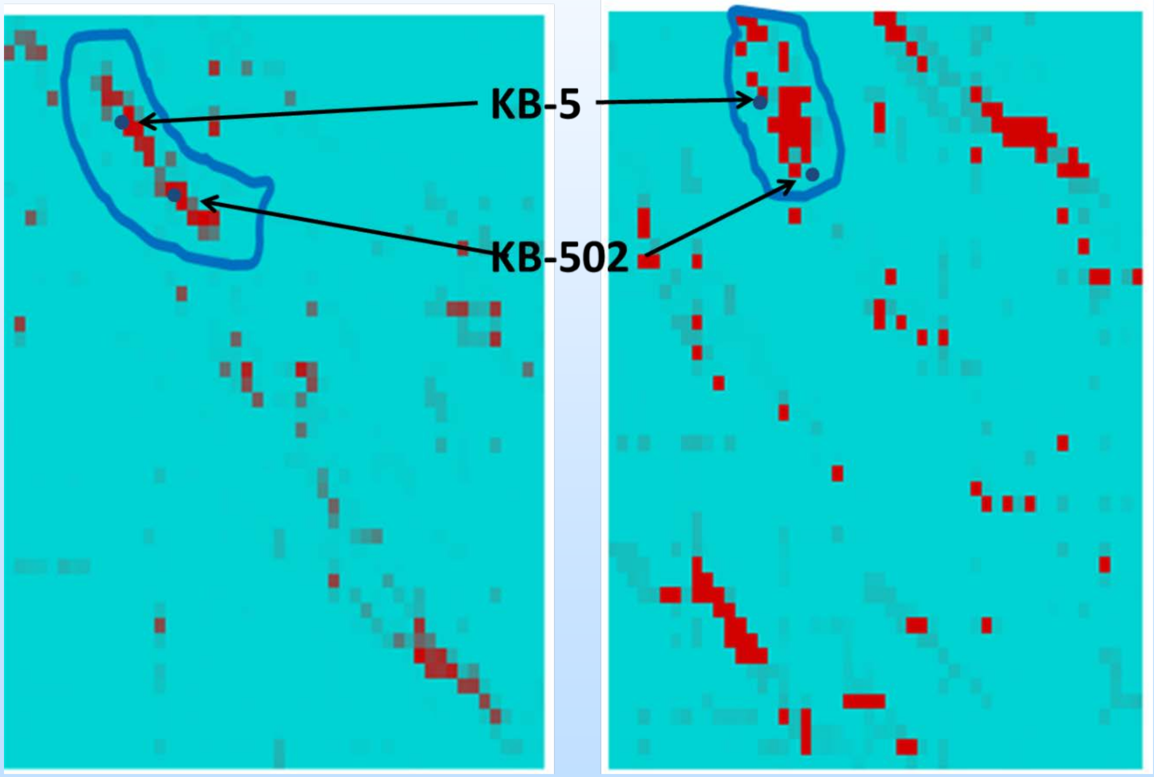
Monitoring locations using PCA defined template



Depth contours, m

Technical Status:
Optimized Proxy Measurement Locations

Application to injection data yields same conclusion: high permeability streaks connect KB-502 and KB-5

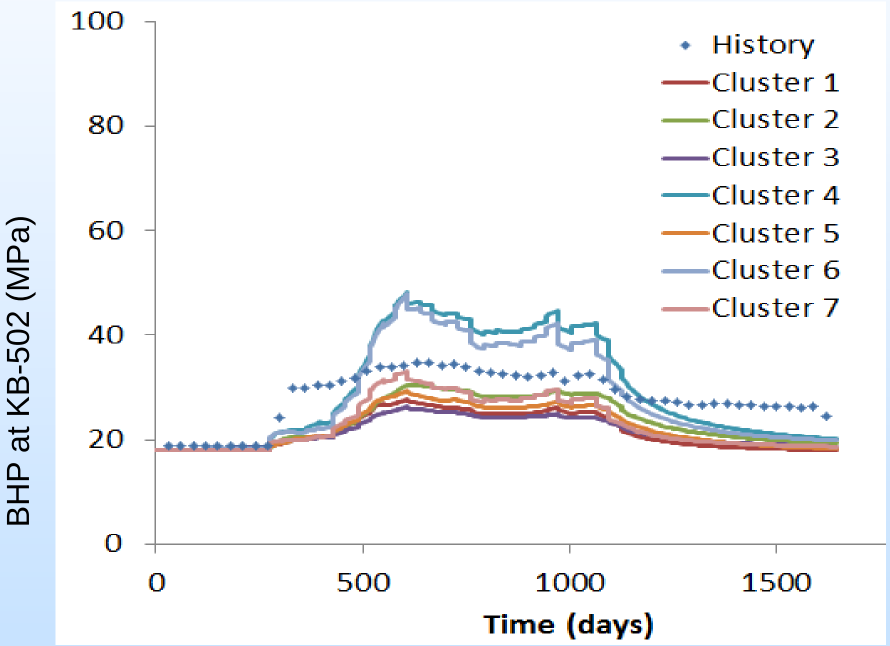


Measurement locations on a square (earlier)

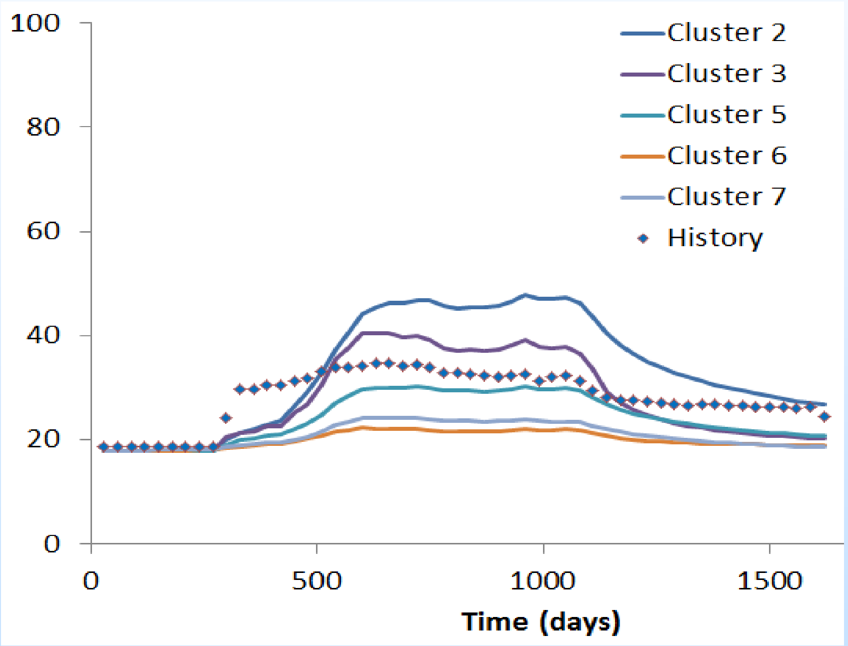
Measurement locations using PCA (new)

Technical Status:
Proxy performance

- Pressure responses show better distribution with new proxy location



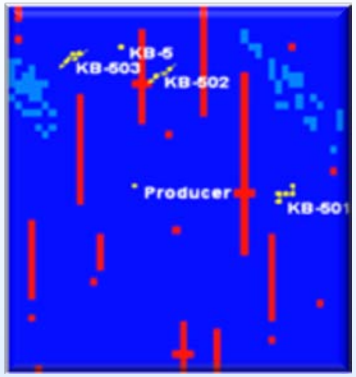
Measurement locations on a square (earlier)

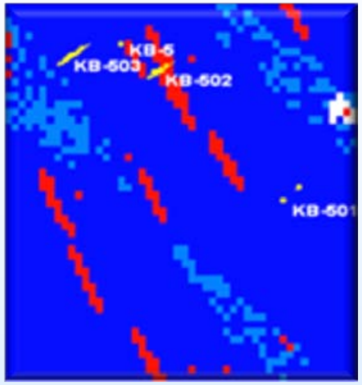


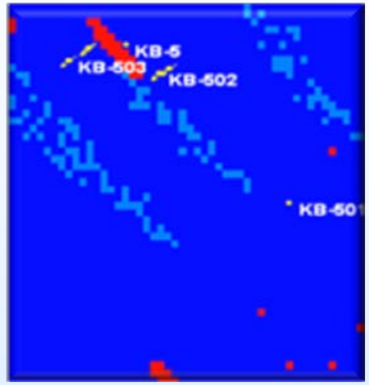
Measurement locations using PCA (new)

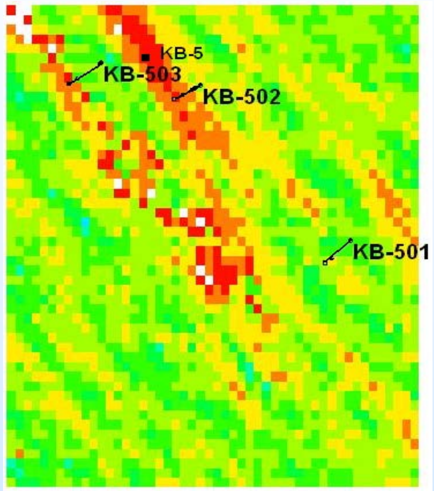
Model Selection Key Result (1)

Models in final cluster exhibit common characteristics that explain field observations

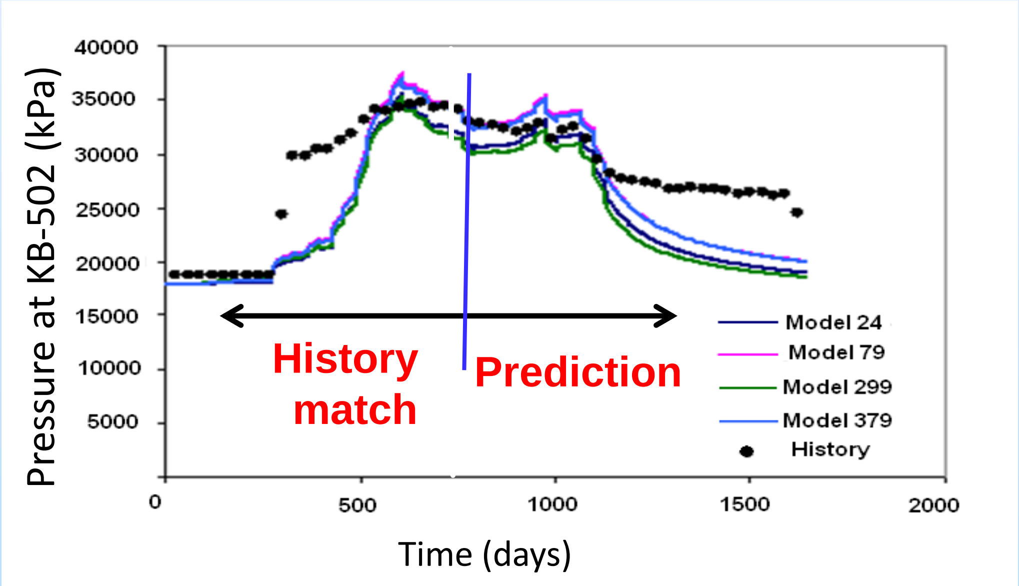






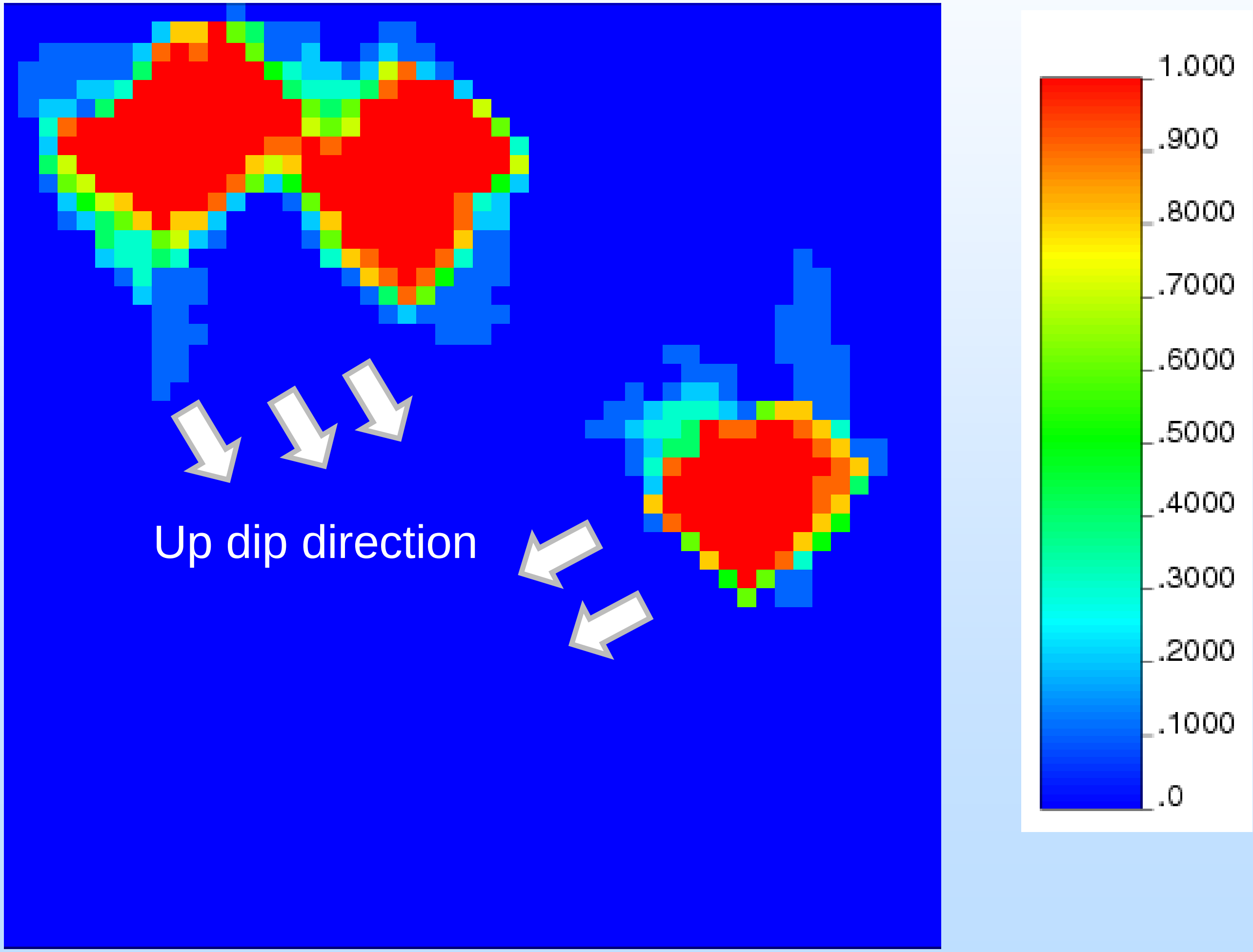


Average of all models from final cluster, showing high permeability streak highlighted over all models



Model Selection Key Result (2)

Probabilistic prediction of plume migration is possible using the models in the final cluster

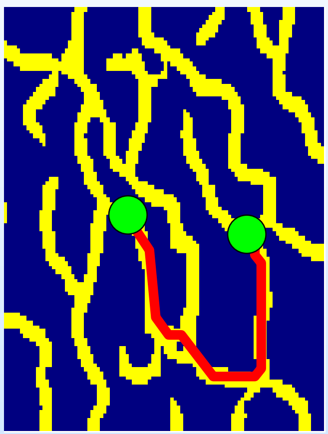


Probability map for CO_2 migration based on the models of the final cluster.

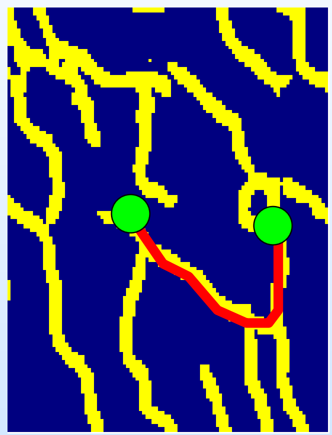
Technical Status:

Connectivity based fast transfer function

- Fast statistical proxy based on shortest connected path between well locations (**Hoonyoung Jeong**)



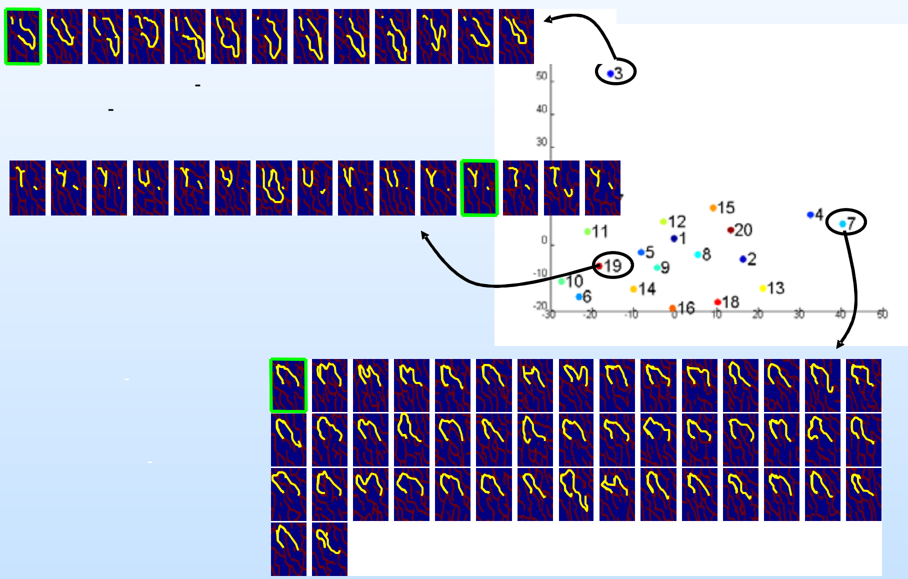
Path A1 of model #1



Path A2 of model #2

permeable facies
impermeable facies
shortest path
Inj / Prod

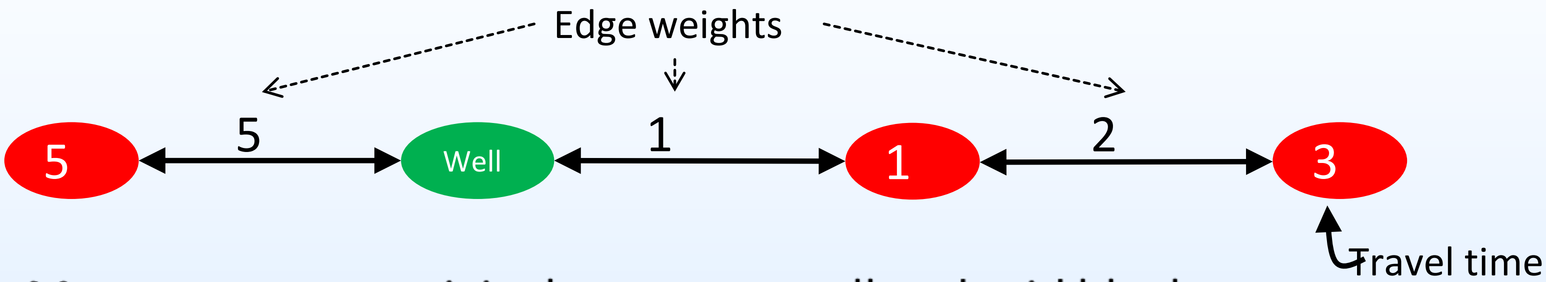
Compute discrete Frechet Distance
(points of path A1, points of path A2)



Models exhibit an orderly transition in connectivity characteristics when projected on a metric space

Technical Status:
Connectivity Analysis of Models

- Connectivity analysis



- Measure a connectivity between a well and grid blocks
- $Edge\ weight = \frac{\sqrt{Vp_i \times Vp_j}}{T_{ij}}$, V_p: pore volume, T: transmissibility

  ➔ travel time of 1 unit viscosity fluid between i[th] and j[th] grid blocks under 1 unit pressure
- Calculate the shortest paths from the well using Dijkstra's algorithm
- Calculate migrated regions by truncating the injected amount in order of travel time
- Can't consider buoyancy and travel time dependent on pressure and viscosity

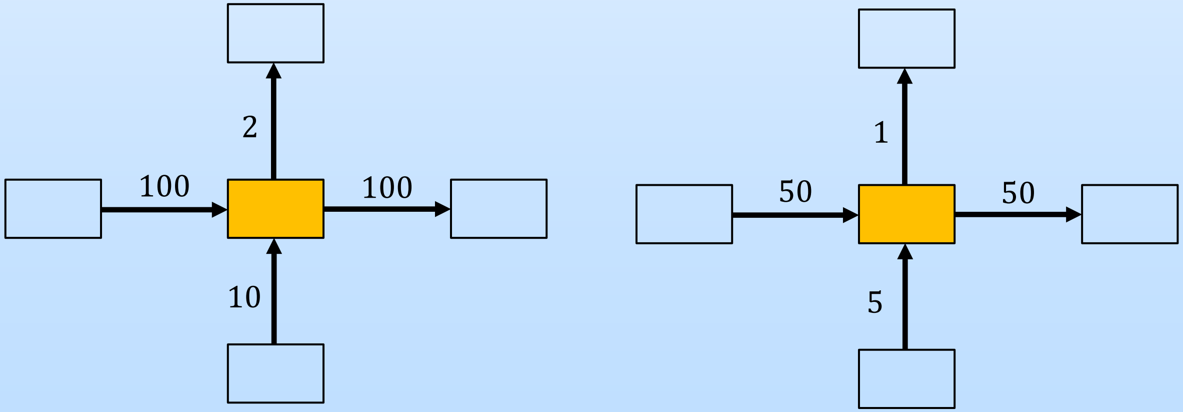
Technical Status:
Modified Connectivity Analysis

- Modify connectivity analysis ➔ scaled connectivity analysis
- Bring potential difference and viscosity

$$Edge\ weight = \frac{\sqrt{Vp_i \times Vp_j}}{T_{ij}} \longrightarrow Edge\ weight = \frac{\sqrt{Vp_i \times Vp_j}}{T_{ij} \times \Delta\Phi} \times \mu_{CO_2}$$

$$\Delta\Phi = \Delta P + \Delta\rho g h$$

  - Calculate rough ΔP from the analytical solution for CO_2 injection in a brine aquifer presented by Mathias *et al.* (2011)
- Use scaled edge weights so that the fluid moves along the edge with the minimum weight at each grid block

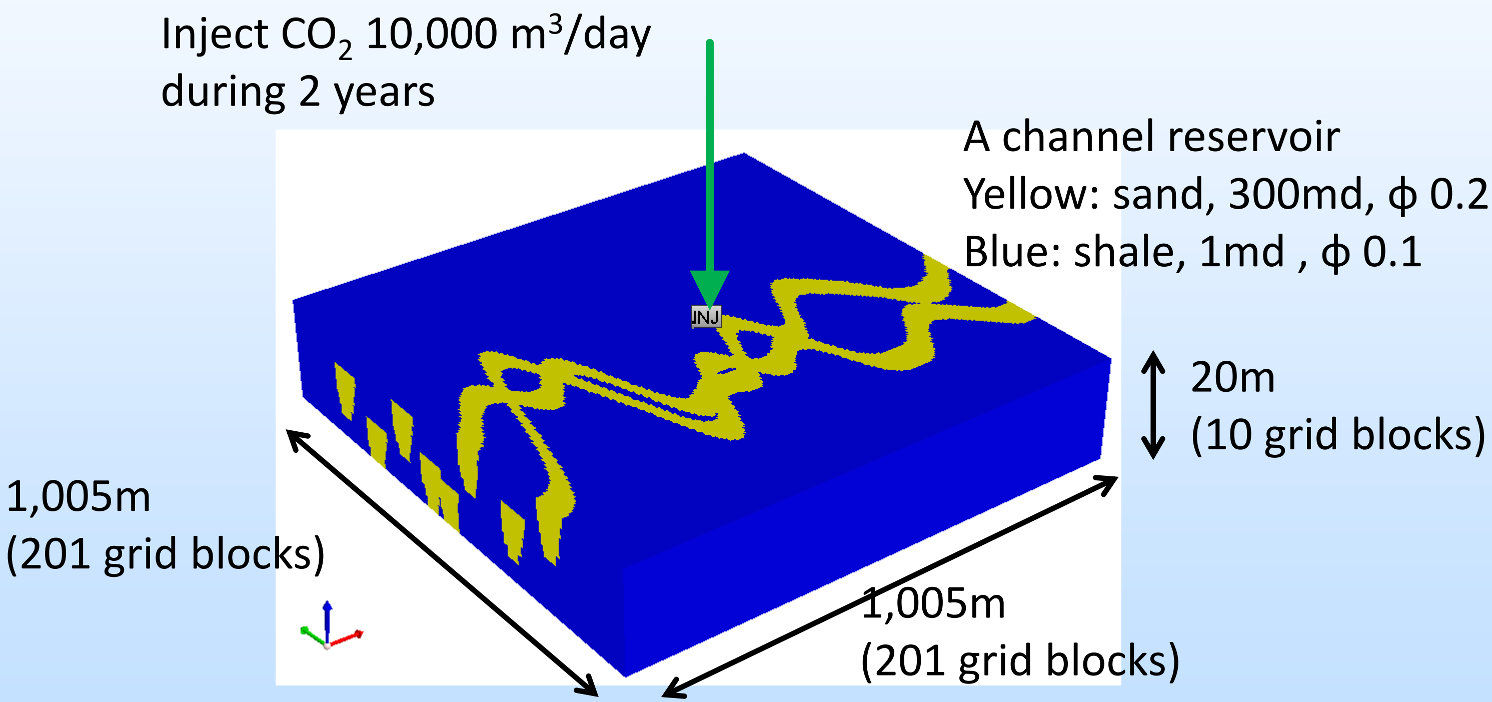


Find the minimum edge weight among the edges connected to a grid block
The edge weights are divided by the minimum value

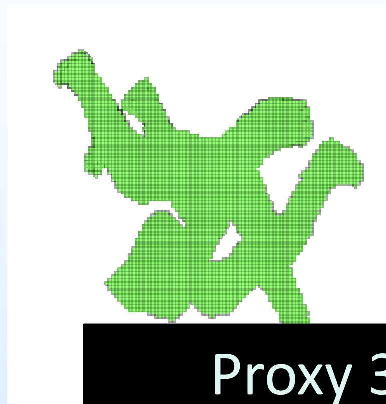
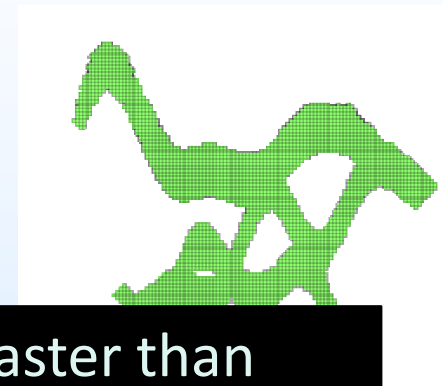
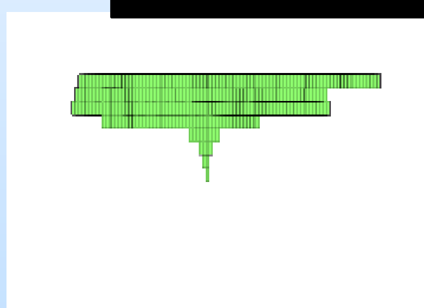
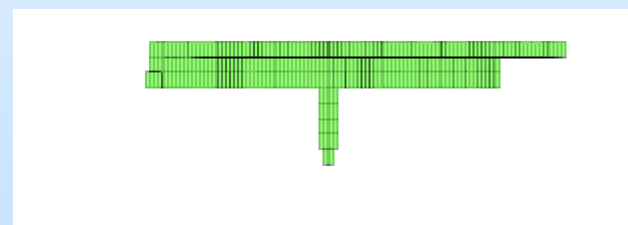
Technical Status:

Application of Modified Connectivity Analysis

- Synthetic field



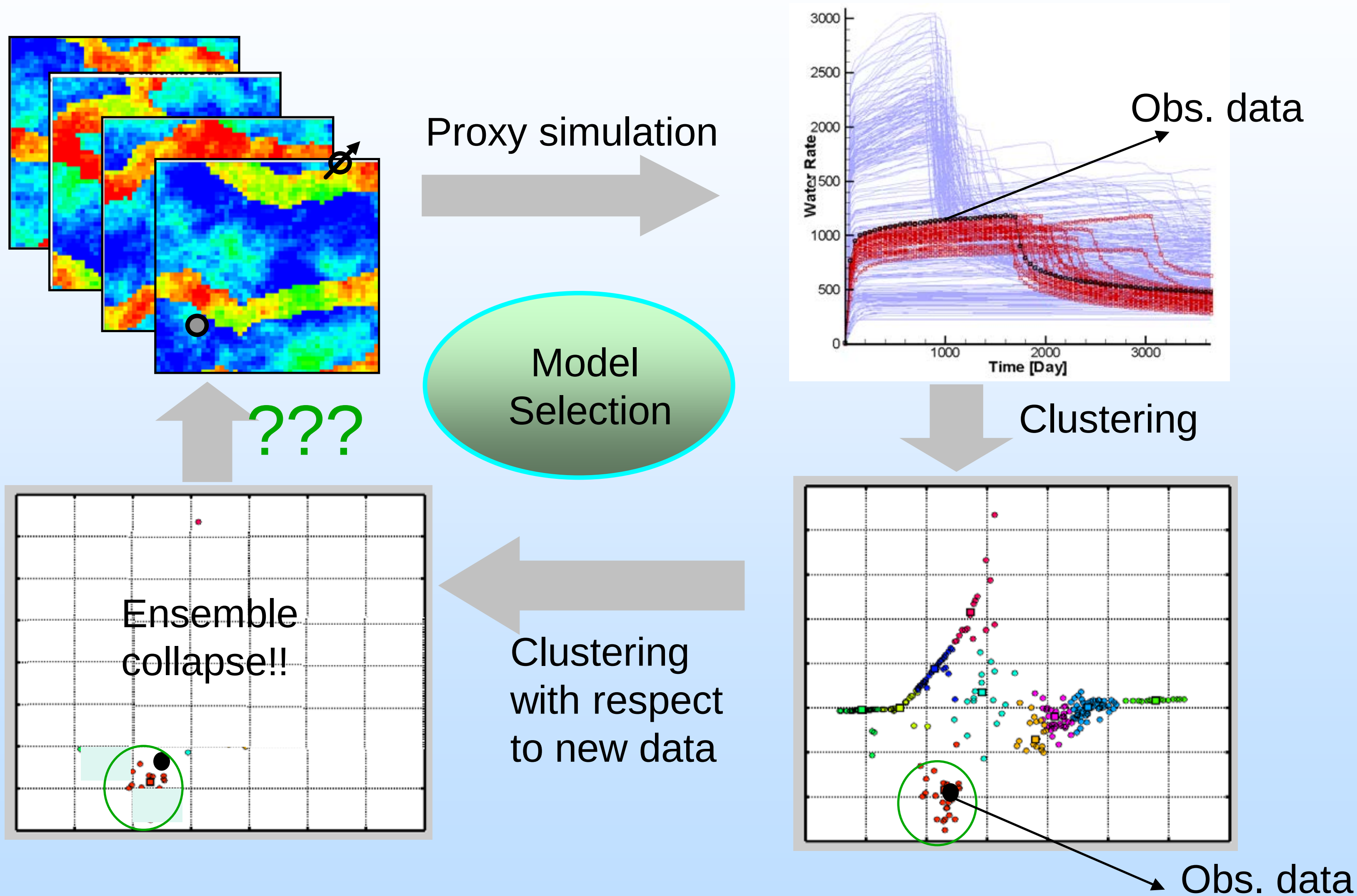
Connectivity Analysis Key Result

	Migration path by CMG (Sat_{CO_2}>0.01)	Approximate migration path by our proxy
Top view		
Side view		
Computation time	1254 sec using 6 processors	4.3 sec using 1 processor

Proxy 300 times faster than simulator in this case

Technical Status:

Model Expansion

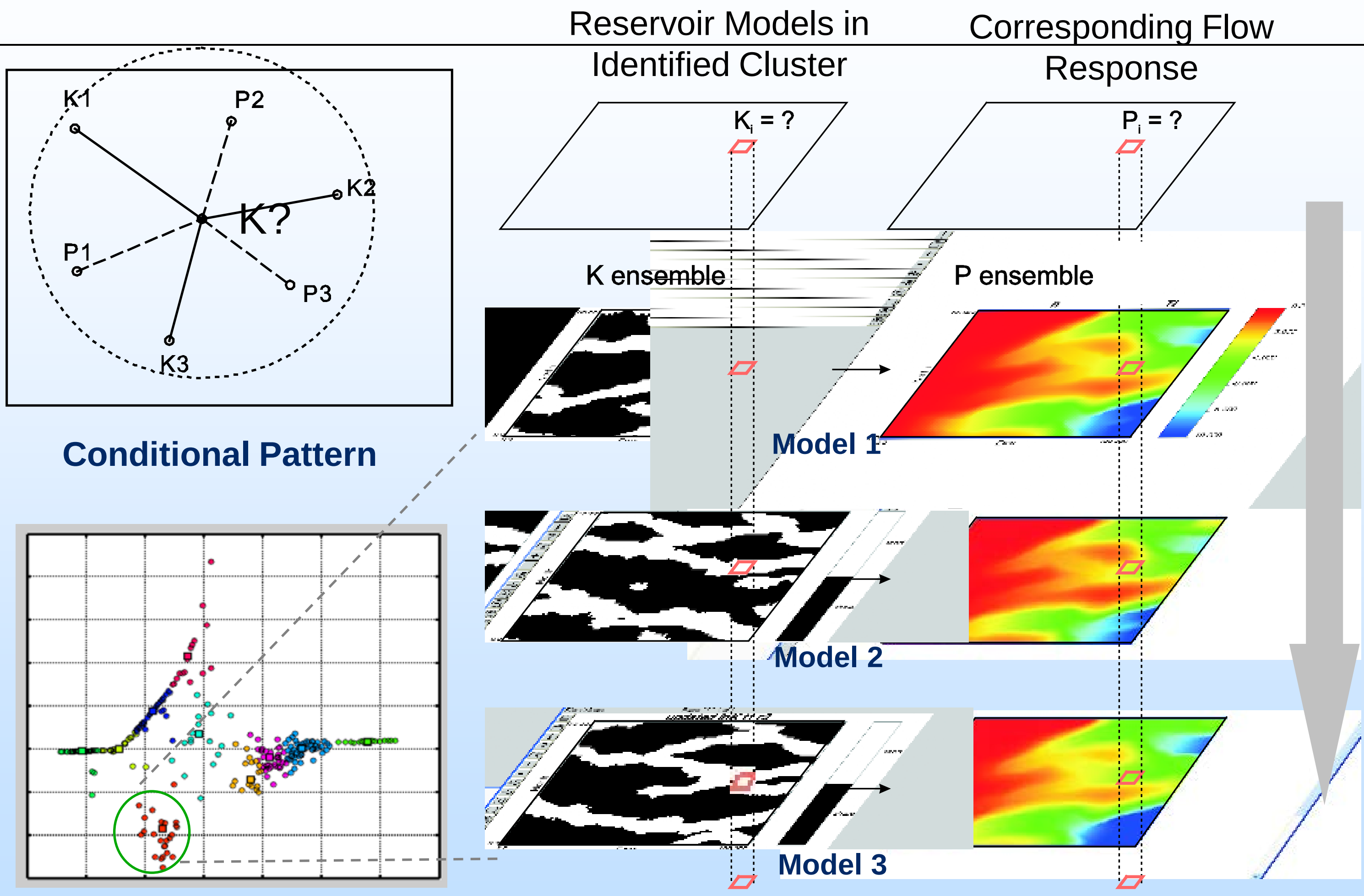


Model expansion is necessary

Technical Status:

Ensemble-based pattern search

(Dr Liangping Li)

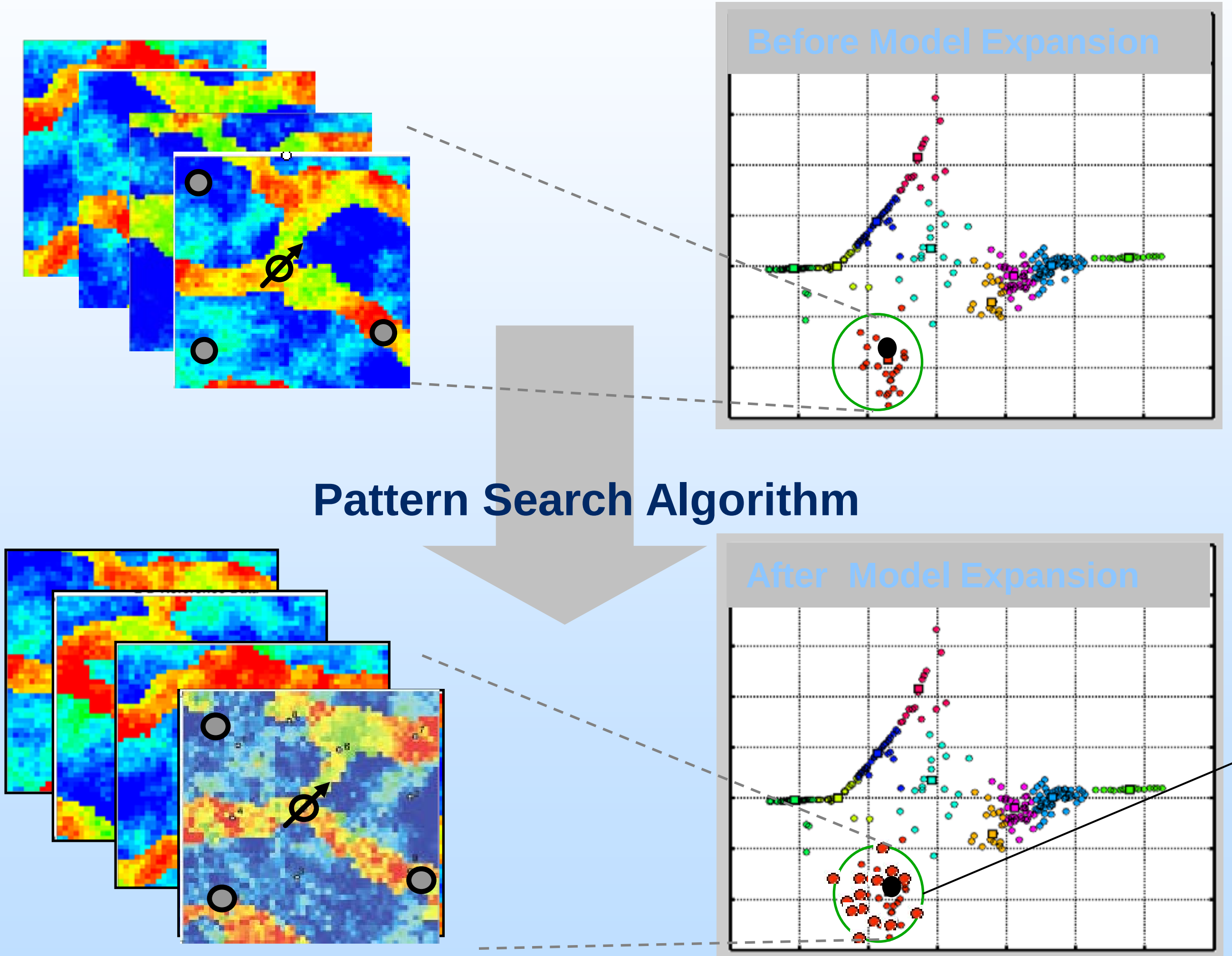


- Sample common conditioning points from the ensemble
- Simulate additional models by searching for conditioning data pattern over the ensemble of selected models

Technical Status:

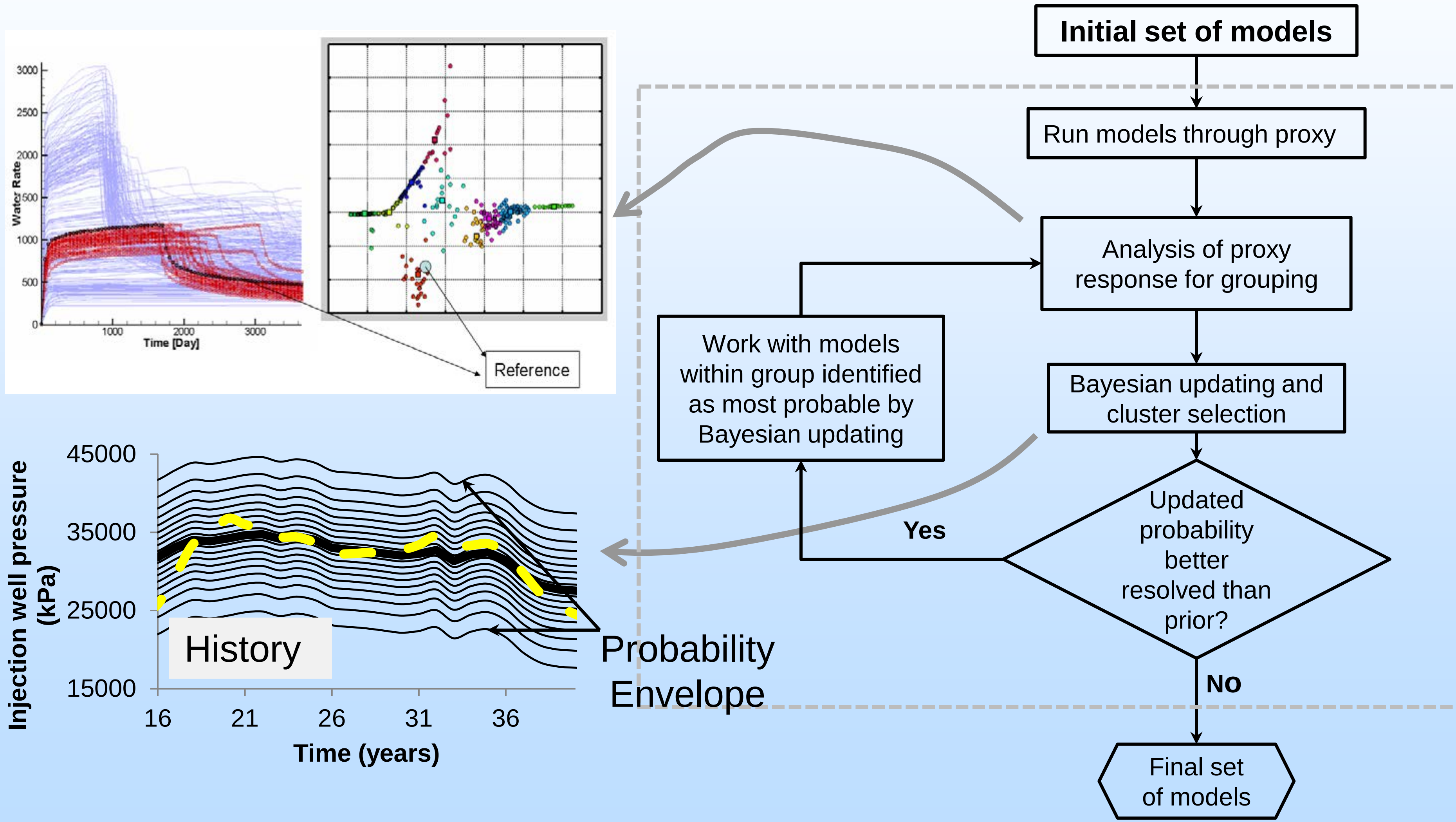
Ensemble-based pattern search

End of iteration



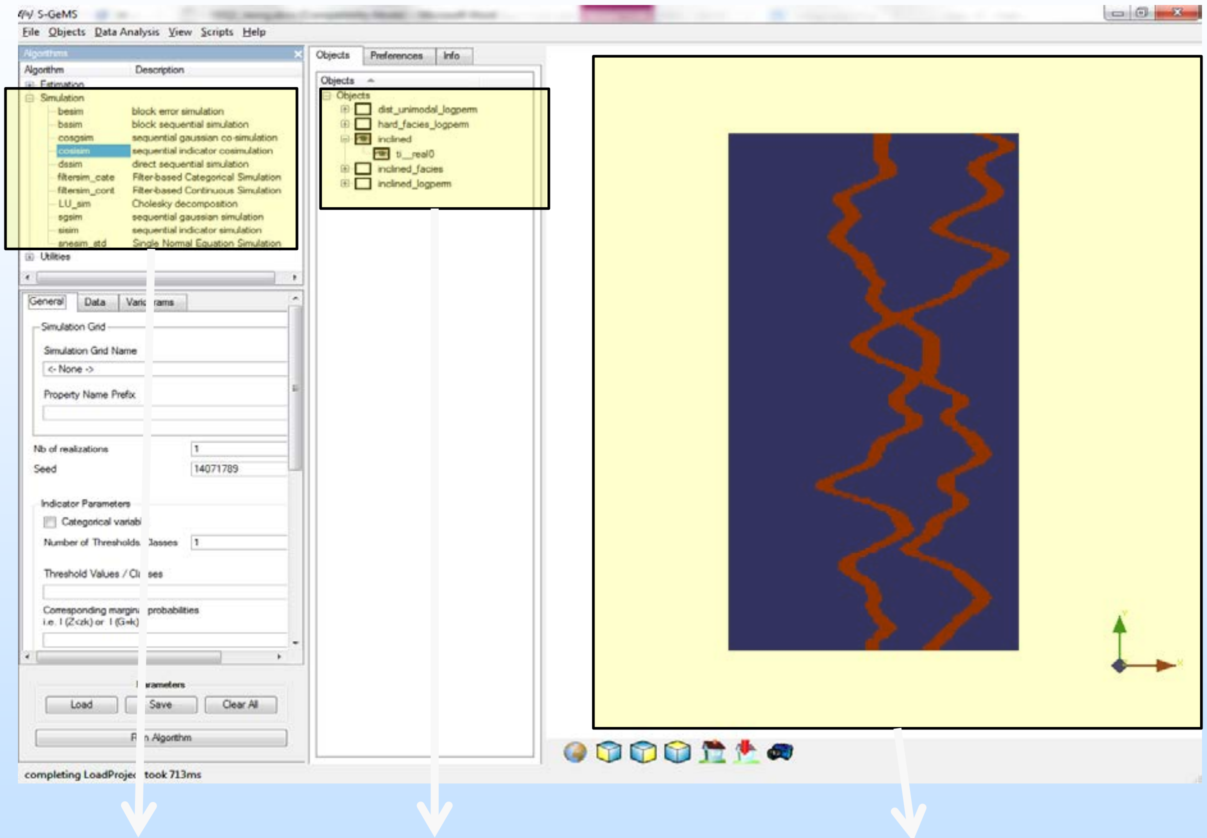
Augmented set of models for next iteration

Technical Status:
Integrated, modular software



Technical Status:

Software Implementation in SGeMS



ALGORITHMS PANEL

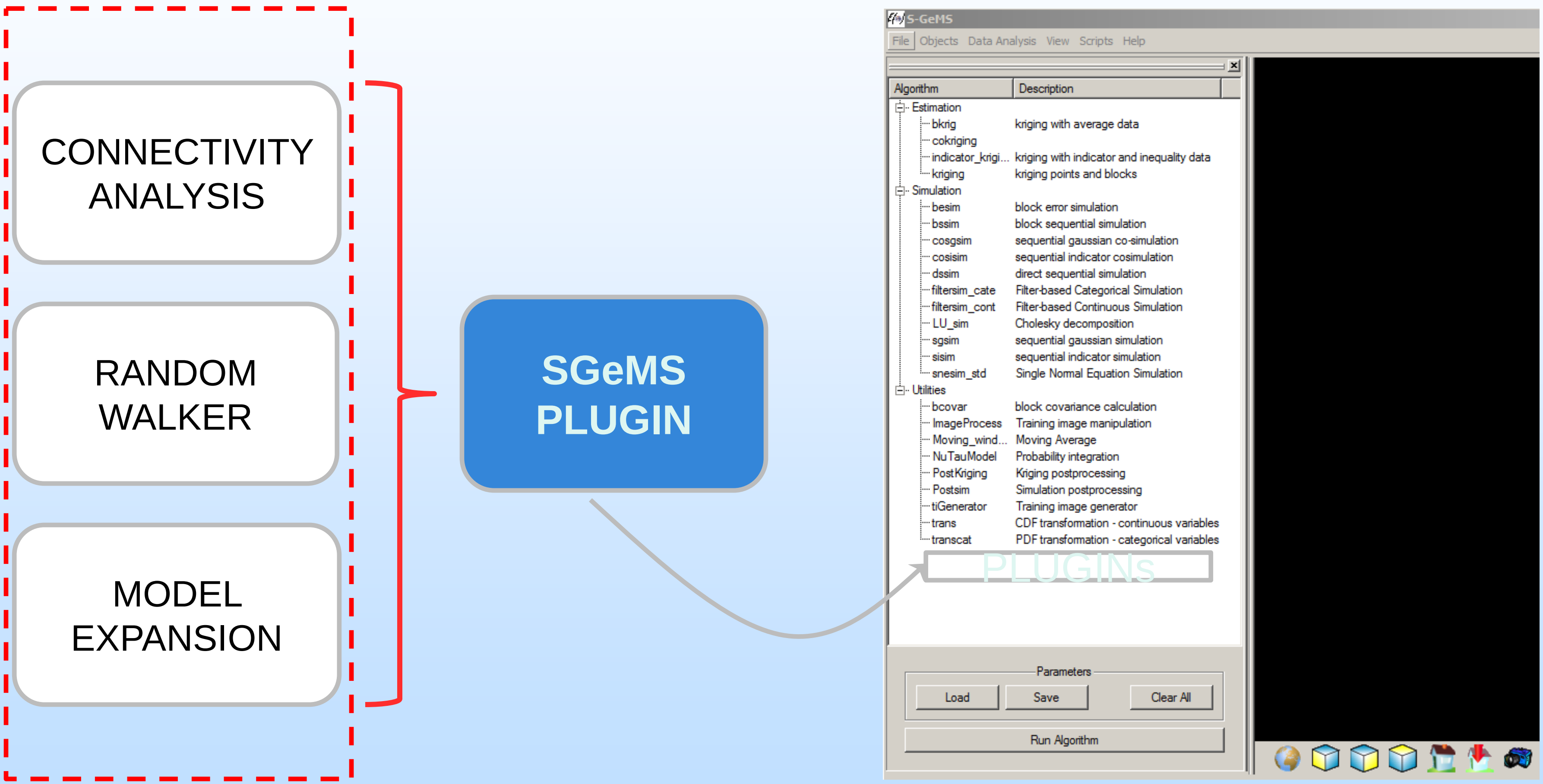
MODELS PANEL

VISUALIZATION PANEL

- **Developed at Stanford University under an Open Source License**
- **We are integrating our algorithms as plugins into SGeMS**

Technical Status:

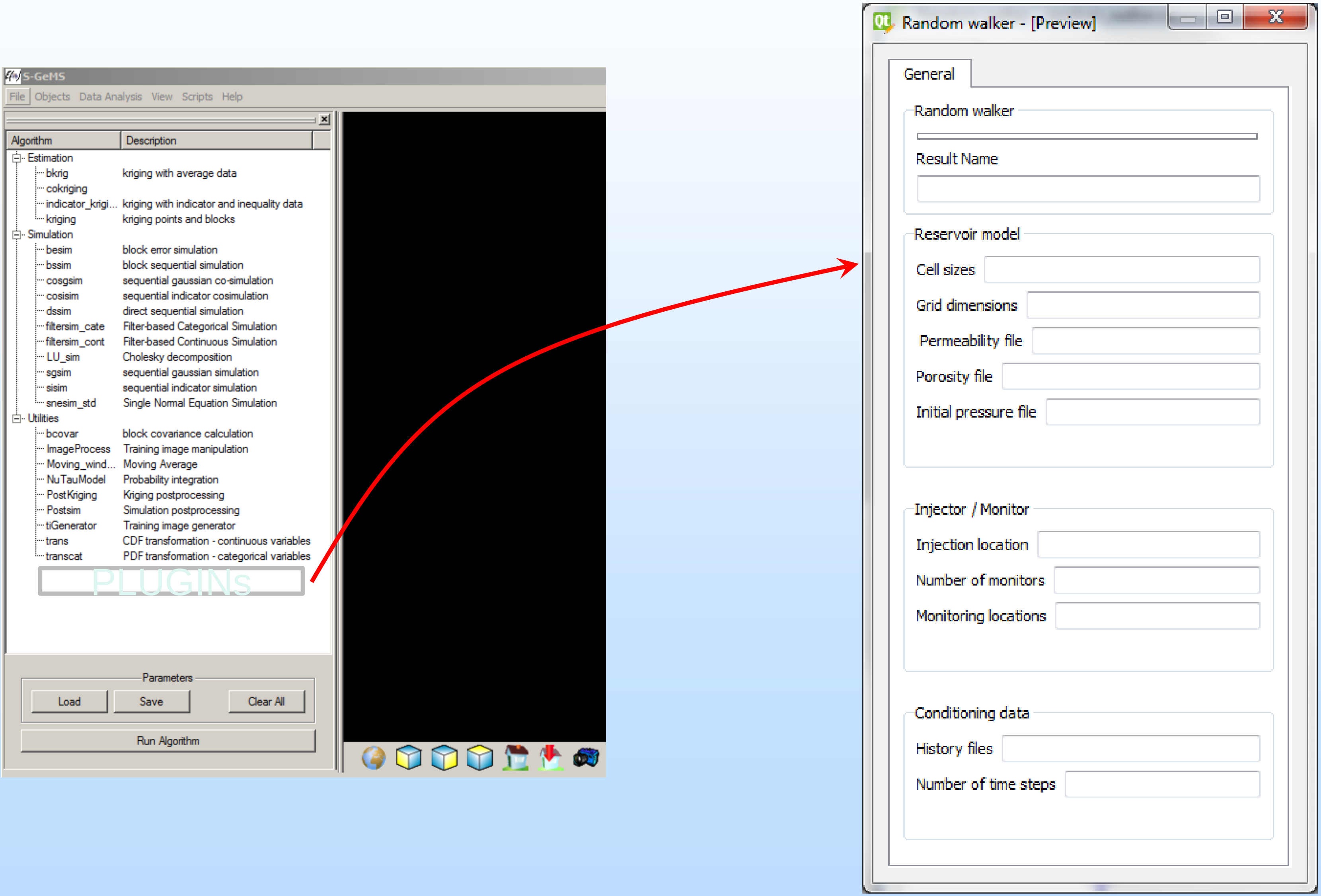
Software Workflow



CODES DEVELOPED IN THIS PROJECT

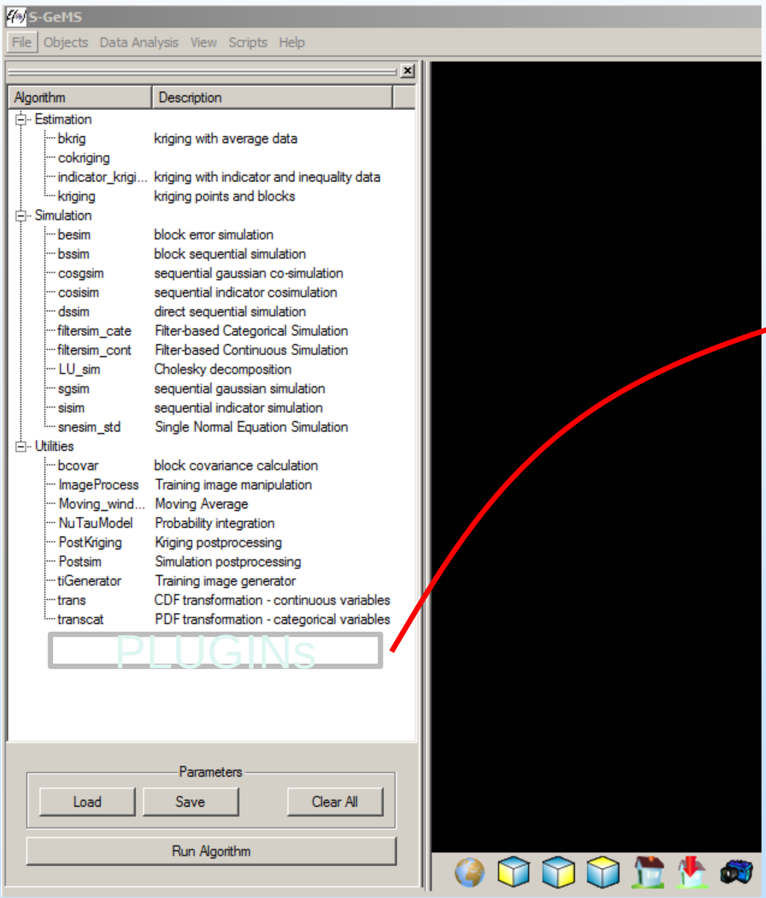
Technical Status:

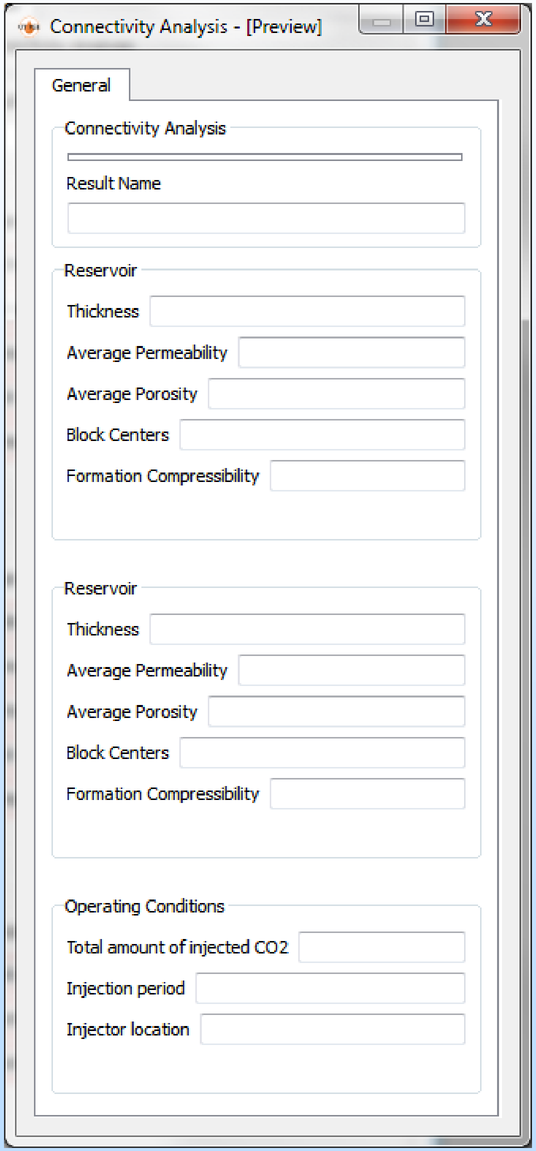
Plugin for Fast Physics-based Proxy



Technical Status:

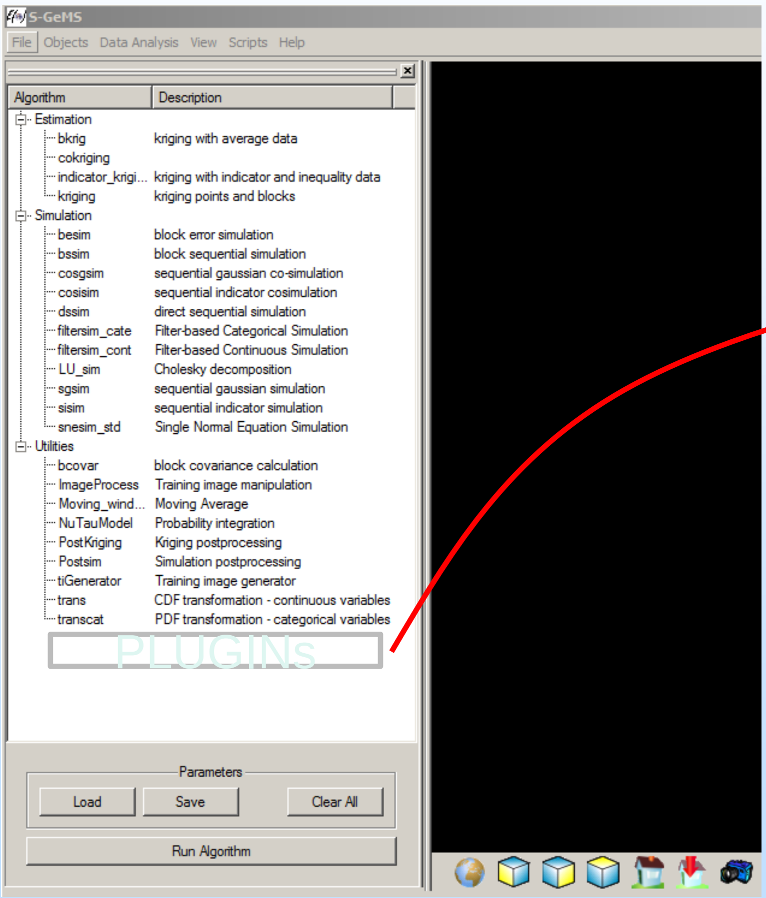
Plugin for Connectivity Analysis

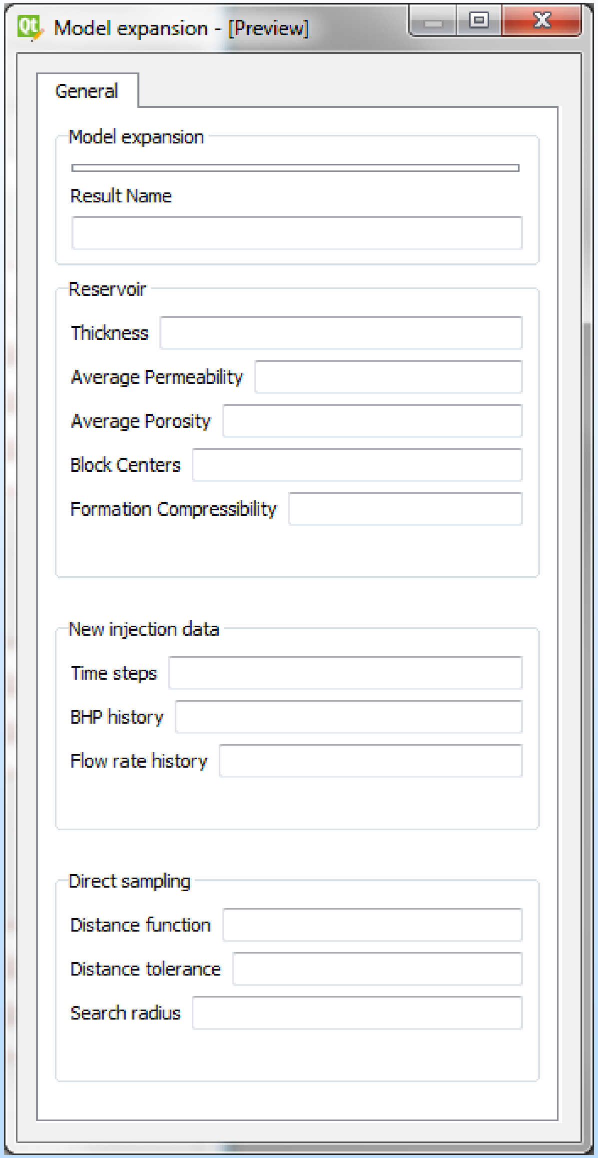




Technical Status:

Plugin for Model Expansion

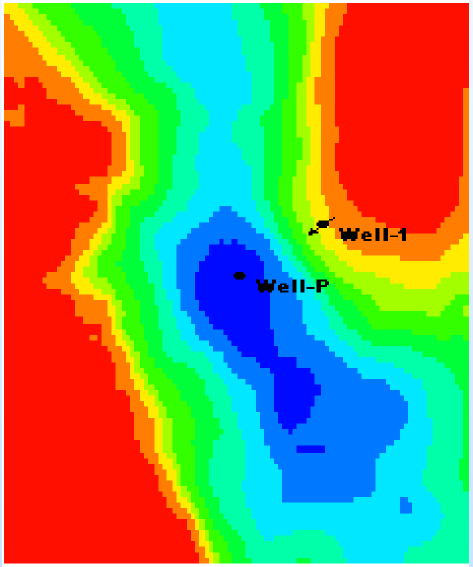




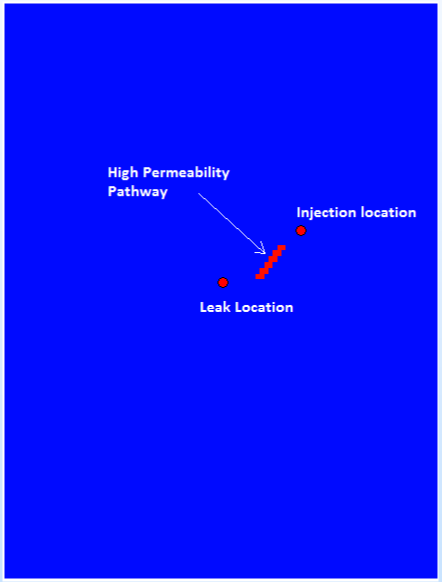
Technical Status:

Effect of Unknown Leak on Model Selection

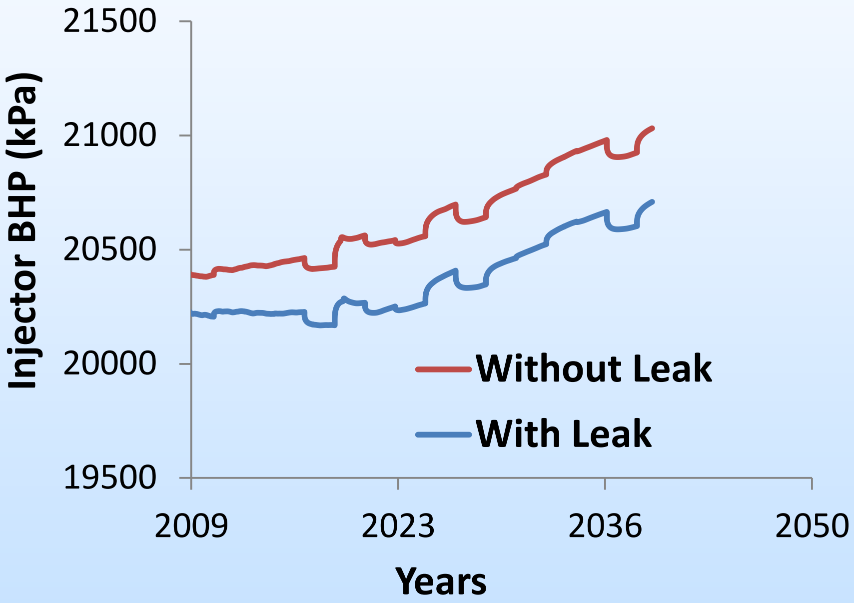
- Objective: can model selection resolve high permeability streak if leak exists somewhere in the storage formation?



Krechba Reservoir Model



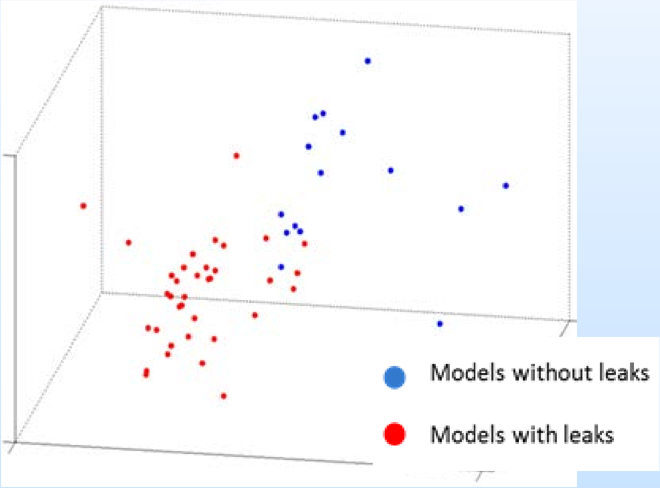
Location of injector, streak and leak



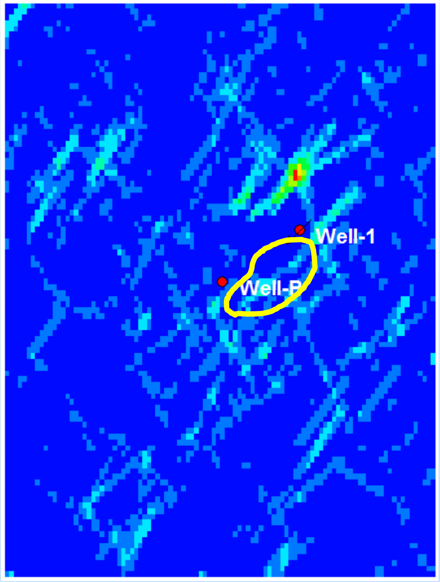
Results indicate that the presence of a leak has a noticeable effect on injection well pressure

Technical Status:
Effect of Unknown Leak on Model Selection

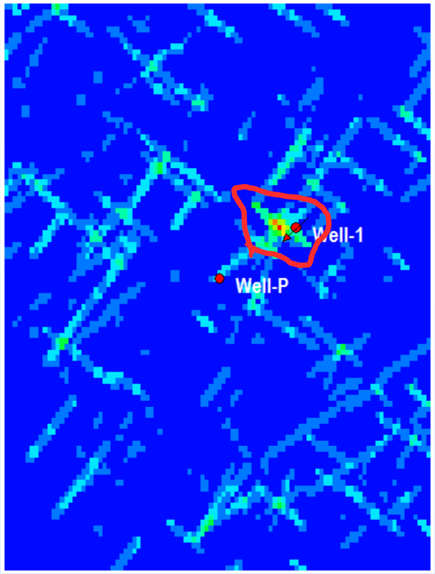
- Clusters of models identified with, without leak are different!



Model clusters in PCA space with and without a leak



Streak modeled in the vicinity of the injector when there is no leak



Streak not crisply resolved when there is a leak

Accomplishments

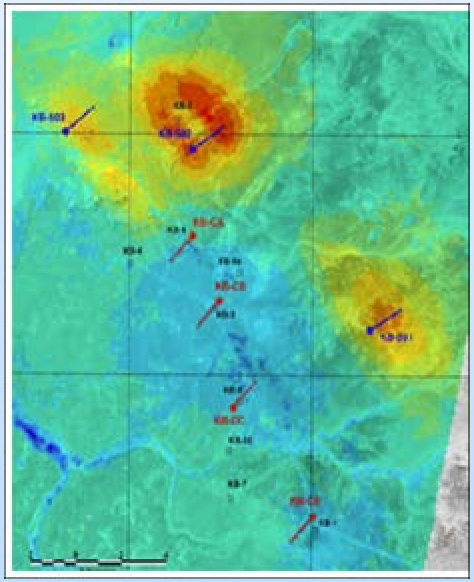
- Sensitivity analysis of impact of subsurface heterogeneity on injection response
- Fast model responses
  - Transport proxy to account for permeability heterogeneity, fluid compressibility, buoyancy effect
  - User no longer required to define proxy monitoring locations in advance
  - Connectivity proxy extended to account for buoyancy
    - Good estimate of plume path
    - Much faster than full-physics simulation
- Effective model classification
  - PCA, Kernel PCA, Multi-dimensional scaling methods
- Method for keeping set of models from collapsing
- Platform for software development identified
  - Plugins for model selection modules defined

Summary

- Key Findings
  - Injection data carry useful information
    - Sensitive to large geologic heterogeneities
    - Can be used to predict future plume migration
  - Combination of efficient proxy, rigorous model classification scheme enables quantitative uncertainty assessment
    - Useful for monitoring process
    - Valuable in managing process
  - Identifying heterogeneities in presence of storage formation leaks is challenging
  - Open source platform (SGeMS) suitable for model selection software
- Lessons Learned
  - Automated selection of proxy monitoring locations works
  - Point-sink leaks (e.g. wells) blur large heterogeneities
    - Raises possibility of refining method to apply to leak detection

Future Work

- Test software on synthetic cases
- Apply software to predict plume movement in In Salah and Utsira/Sleipner
- Extend Model Selection approach to incorporate information from surface deflection data

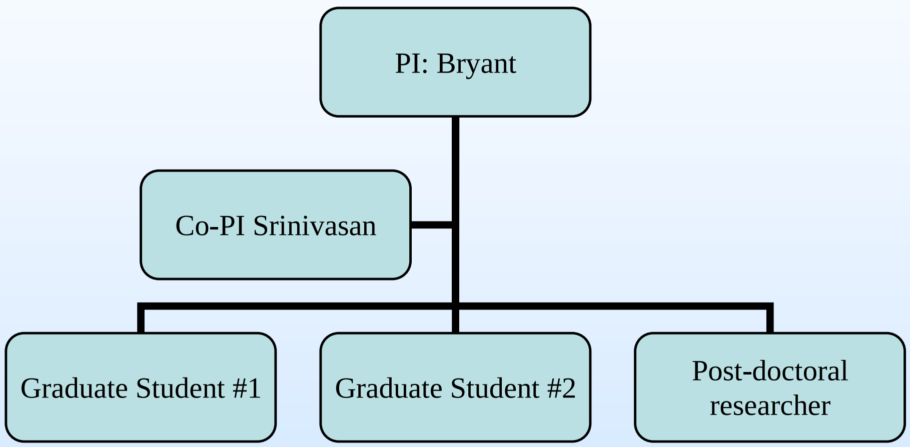


Appendix

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

Organization Chart

- Team:
  - PI Steven Bryant
  - Co-PI Sanjay Srinivasan
  - Researchers
    - Sayantan Bhomik
    - Hoonyeong Jeong
    - Dr Liangping Li



- Organization
  - Center for Petroleum and Geosystems Engineering
  - Cockrell School of Engineering
  - The University of Texas at Austin

Gantt Chart

AUG 2013

BP	Task	Milestone	Y 1				Y2				Y3				Y4		Interdependencies
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	
1	1																Project management
	2	1.A			X												Verify feasibility for Phase 2
	3.1																Pre-requisite for software development in Phase 2
	3.2	1.B				X											
	4.1																Provides geologic consistency to interpretation of injection data
	4.2	1.C								X							
2	5	2.A										X					Combines Tasks 2-4 into software platform
	6	2.B											X				Validates Task 5
	7																Uses BP 1, 2 to quantify uncertainty
3	8.1	3.A													X		Uses BP 2 to apply concept to field data
	8.2	3.B														X	Applies BP 2 to In Salah
			BP 1								BP 2			BP 3			

Phase	Milestone Description	Completion
3	**3.A**: Extending methodology in order to integrate other types of data	Q1 Y4
	3.B: Application of software, method on In Salah data.	Q2 Y4

Bibliography

- Journal, multiple authors:
  - Srinivasan, S., and Jeong, H., 2012, Modeling the Uncertainty in CO_2 Plume Migration During Sequestration Using a Model Selection Approach. Accepted for publication in Mathematical Geosciences.
- Publication:
  - Jeong, H., Srinivasan, S. and Bryant, S.L., 2012, Uncertainty Quantification of CO_2 Plume Migration Using Static Connectivity, proceedings of International Conference on Greenhouse Gas Technologies (GHGT), Kyoto, Japan.
  - Bhowmik, S., Srinivasan, S. and Bryant, S. “Prediction of plume migration using injection data and a model selection approach,” Proceedings of the 11th International Conference on Greenhouse Gas Technologies (GHGT-11) held in Kyoto, Japan, 19-22 Nov. 2012.
  - Bhowmik, S. “Predicting the migration of CO_2 plume in saline aquifers using probabilistic history matching approaches.” MS Thesis, The University of Texas at Austin, 2012.
  - Bhowmik, S., Srinivasan, S. and Bryant, S., “Predicting the Migration of CO2 Plume Using Injection Data and a Distance-Metric Approach to Reservoir-Model Selection,” SPE 139709-PP prepared for presentation at the SPE International Conference on CO2 Capture, Storage, and Utilization held in New Orleans, Louisiana, USA, 10–12 November 2010.
  - Bhowmik, S., Srinivasan, S. and Bryant, S., “Inferring migration of CO_2 plume using injection data and a probabilistic history matching approach,” Proceedings of the 10th International Conference on Greenhouse Gas Technologies (GHGT-10) held in Amsterdam, The Netherlands, on 19-23 Sept. 2010. *Energy Procedia* 4, pp. 3841-3848, 2011. DOI: 10.1016/j.egypro.2011.02.320.