

*Inexpensive Monitoring and  
Uncertainty Assessment of  
CO<sub>2</sub> Plume Migration*

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Sanjay Srinivasan

The University of Texas at Austin

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U.S. Department of Energy  
National Energy Technology Laboratory  
Carbon Storage R&D Project Review Meeting  
Developing the Technologies and  
Infrastructure for CCS  
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# Presentation Outline

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- Project Overview
- Technology Benefits
- Technical Status
- Wrap up
  - Key accomplishments
  - Lessons learned, future plans

# Benefit to the Program

- **Project Objective:** new technique for probabilistic assessment of CO<sub>2</sub> plume migration based on paradigm of geological model-selection using injection data

## **Program Goal Supported**

*Develop and validate technologies to ensure 99 percent storage permanence.*

- **Project Benefits Statement**

The project is developing a modular software for quantifying the uncertainty in predicting CO<sub>2</sub> plume migration using injection data. The technology is based on grouping geologic models based on connectivity characteristics and subsequently performing model selection within a Bayesian framework using injection data.

**The development of a cost-effective technique for enhanced monitoring will enable proactive remediation of plume migration direction so as to ensure 99% containment**

# Project Overview: Goals and Objectives

- **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 monitor and verify if 99 percent of injected CO<sub>2</sub> remains in the injection zones*

# Project Overview:

## Success Criteria

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### **Quantitative assessment of information in injection data**

- Development of screening tool for assessing impact of geology on injection response

### **Classification technique for accurately grouping models based on similar connectivity characteristics**

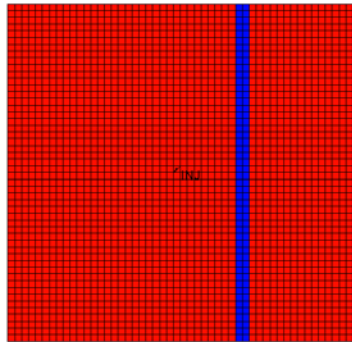
- Software with several options for model classification, PCA, MDS etc and several proxies for assessing reservoir connectivity

### **Robust assessment of uncertainty in predicting plume migration path**

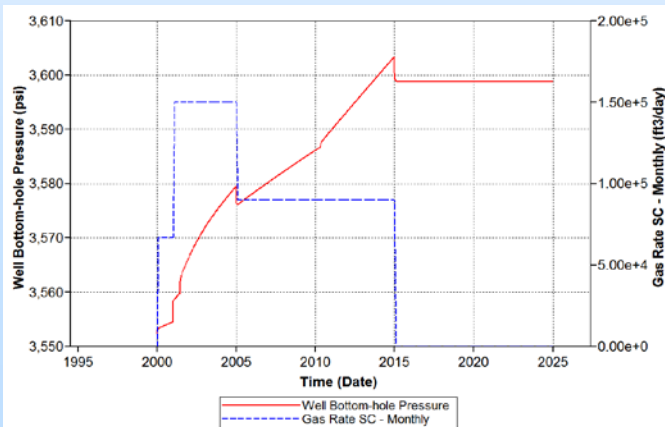
- Implementation of model resampling to enhance the selection of models within a selected cluster so that the problem of model collapse is avoided
- Deployment of a modular software for plume monitoring that could be integrated with existing tools and frameworks for risk assessment

# Technical Status

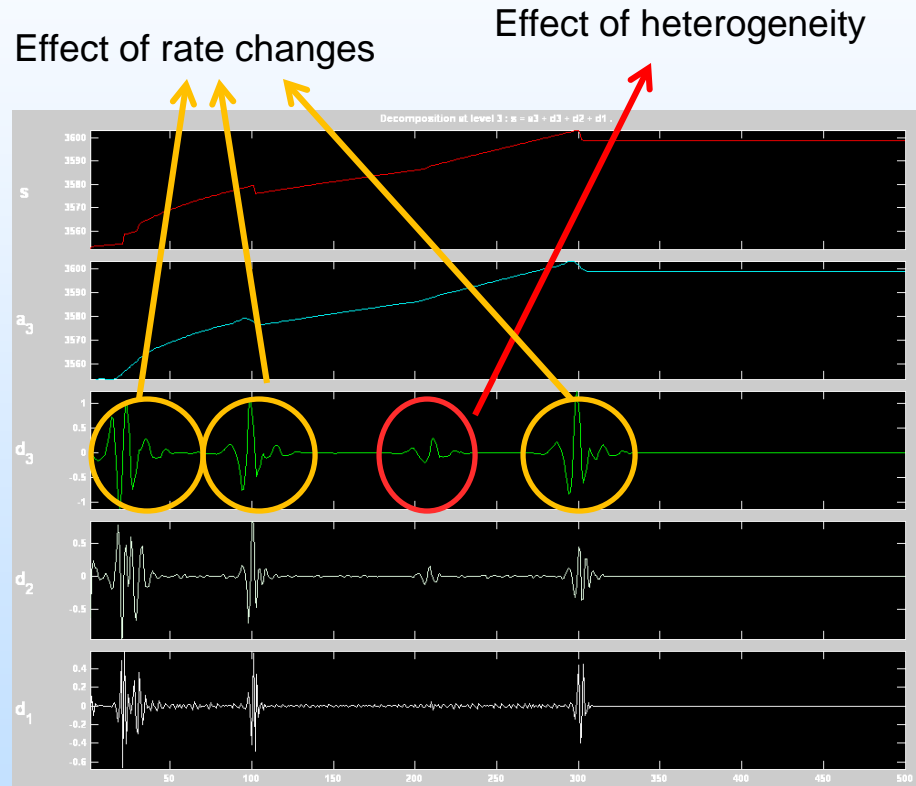
Assessment of heterogeneities with detectable signatures



Permeability Heterogeneity



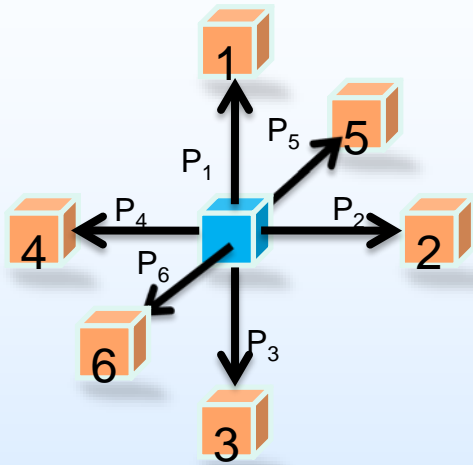
Rate Fluctuations



Wavelet Analysis using Daubechies wavelet

# Technical Status

Development of a physical Proxy and validation cases



Particle Tracking Algorithm

Transition probability

$$P_{transition_{i \rightarrow j}} = \frac{velocity\ function_{i \rightarrow j}}{\sum_{\substack{k: neighboring\ locations \\ i: current\ location}} (velocity\ function_{i \rightarrow k})}$$

where

$$velocity\ function = v_{BL} \times v_{macro} \times (1 + f_w)$$

Specific velocity

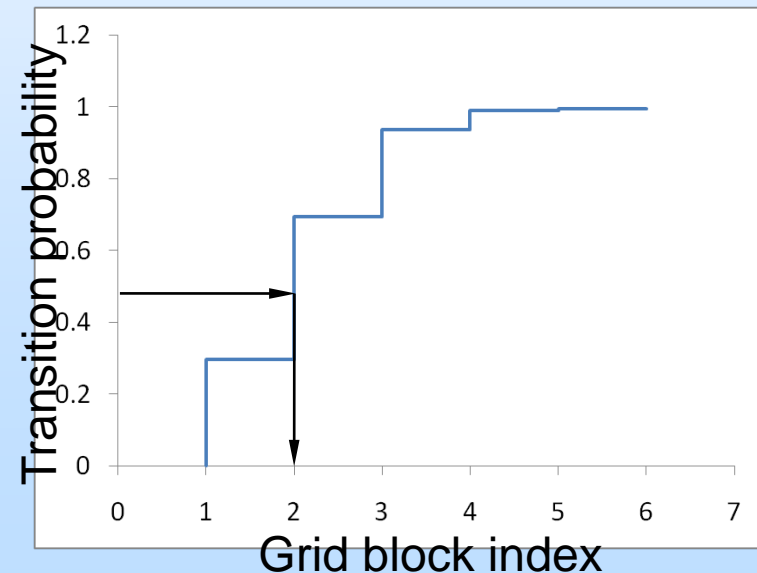
Darcy velocity

Fractional flow value

$$v_{macro} = \frac{[\Delta P + \Delta \rho g \Delta z] k_{avg, i \rightarrow j}}{\mu_{CO_2} L}$$

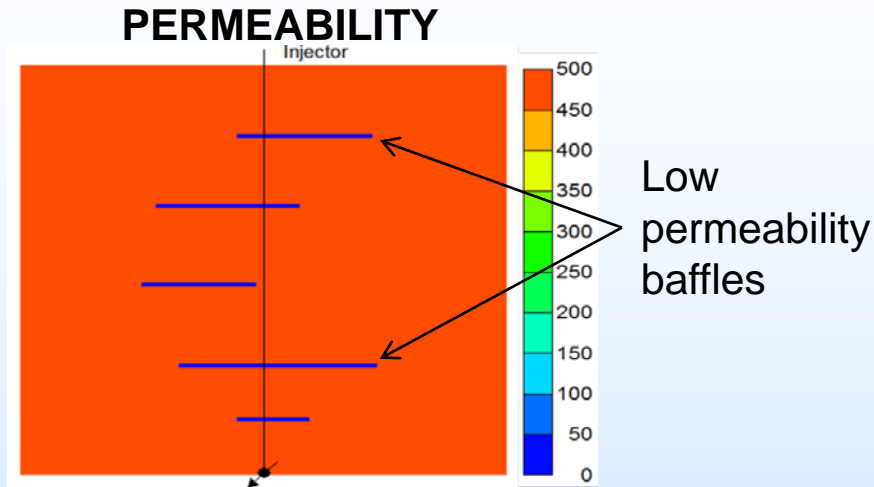
$$\Delta P = \frac{q B \mu}{4 \pi k_{avg, path} L_{path}} \operatorname{erfc} \left( \sqrt{\frac{\phi \mu c_t L_{path}^2}{4 k_{avg, path} t}} \right)$$

Raghavan 1993



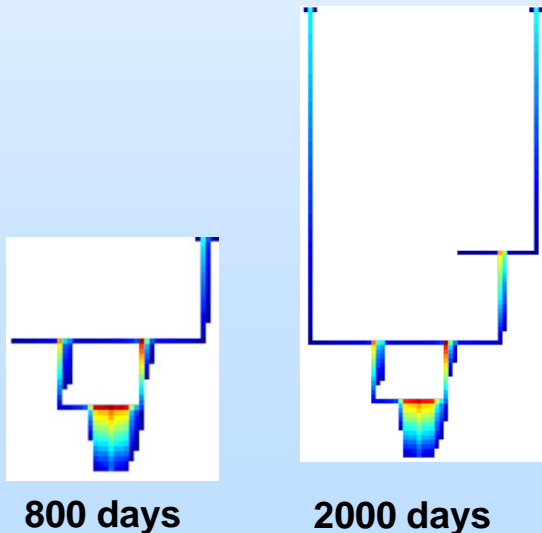
# Technical Status

## Proxy Verification

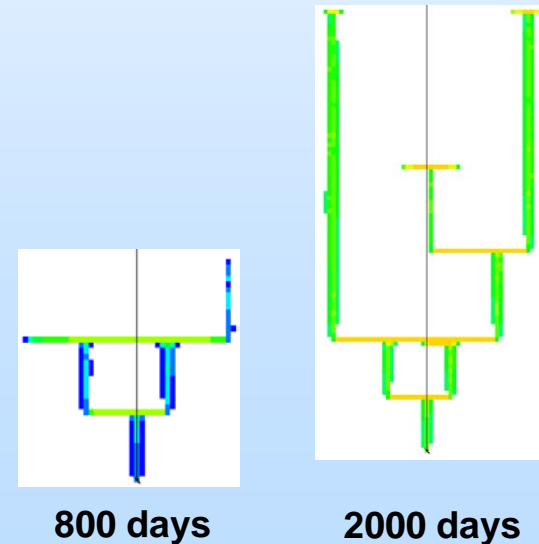


### SYNTHETIC MODEL:

- Test proxy in gravity dominated flow
- 101 x 1 x 100 grid blocks
- Uniform permeability (500 mD) with low permeability baffles (0.1 mD)



**Proxy result**



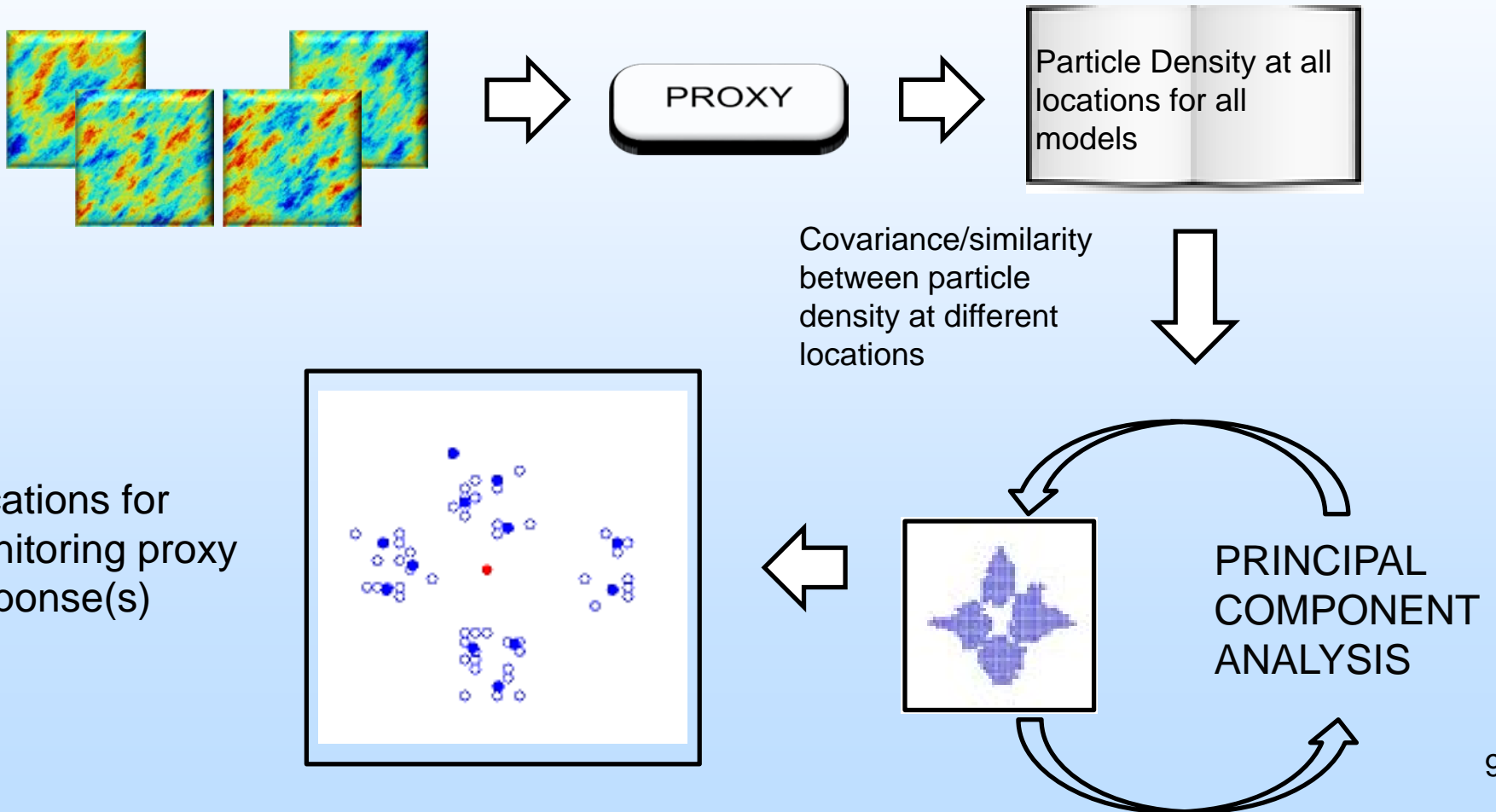
**Numerical simulation result**



# Technical Status

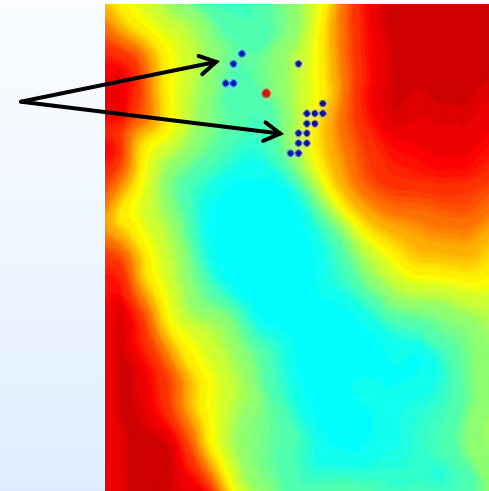
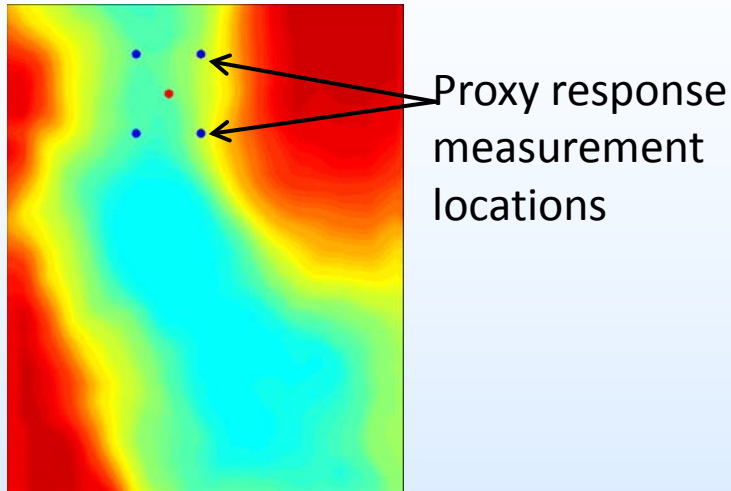
Proxy Measurement locations

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



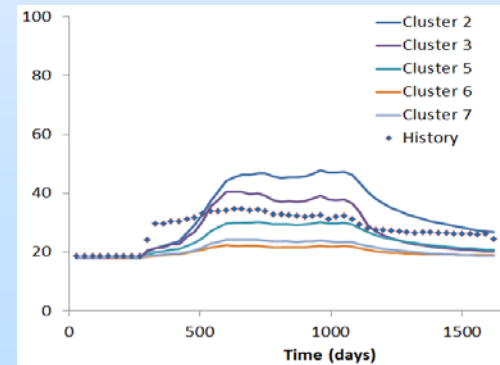
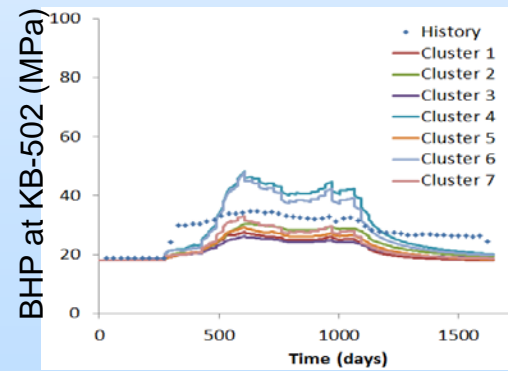
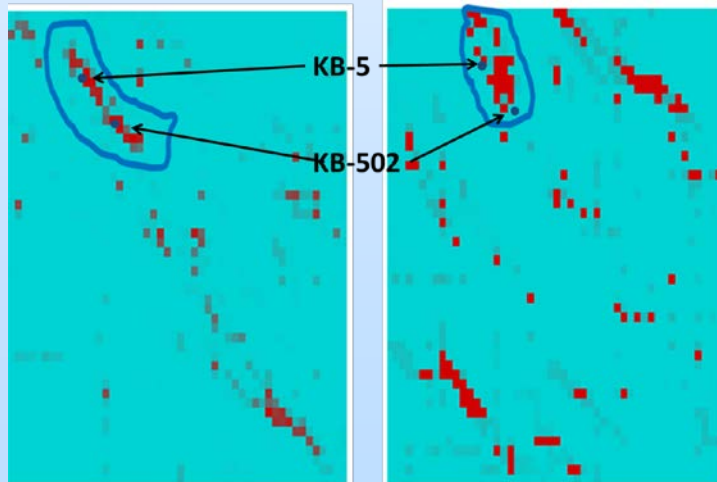
# Optimizing proxy monitoring locations

- Monitoring locations using new method for Krechba



Monitoring locations on a square template

Monitoring locations using PCA defined template

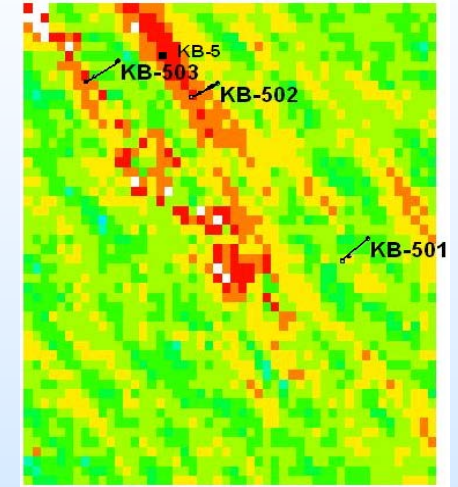
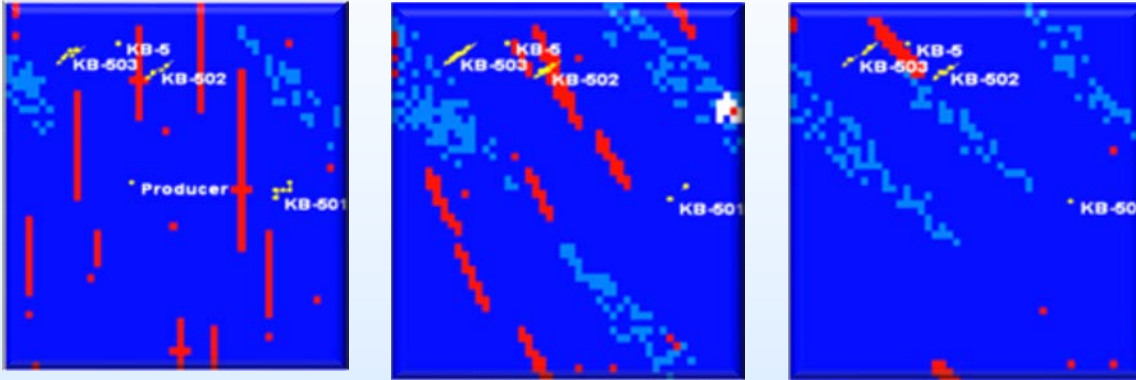


**Model Selection Results Similar for both cases**

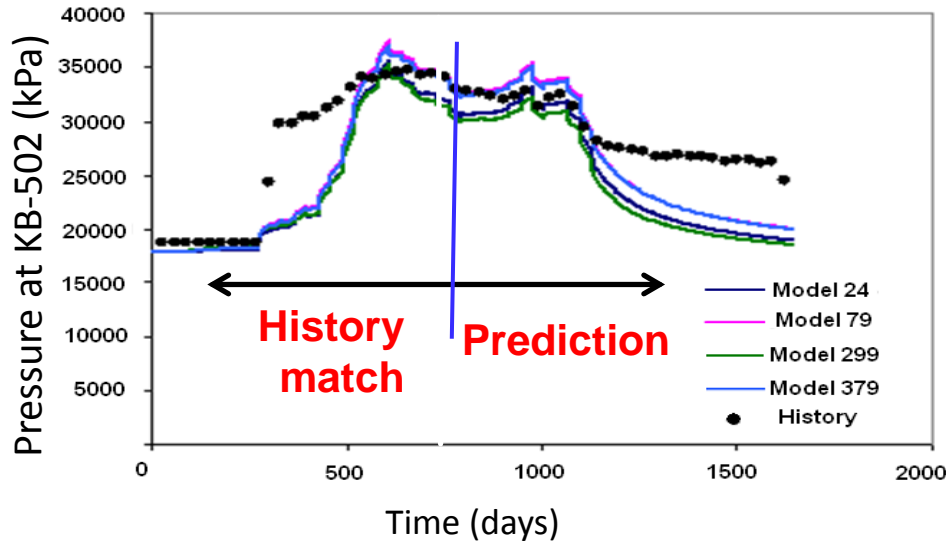
# Technical Status

## Key Result

Selected models in final cluster exhibit common characteristics that explain field observations

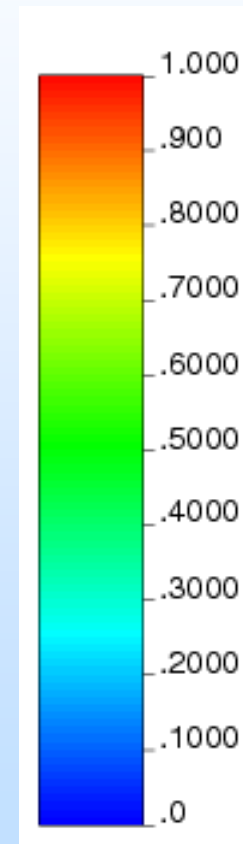
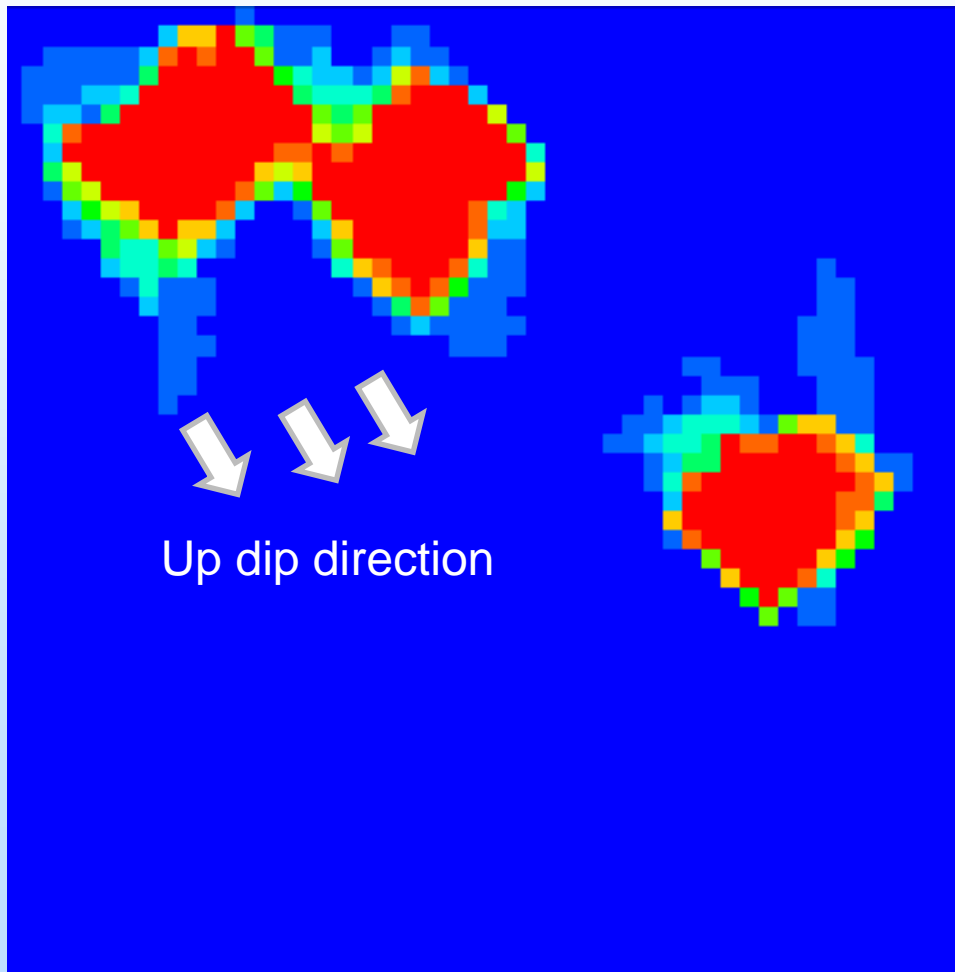


Average of all models from final cluster, showing high permeability streak highlighted over all models



# Technical Status

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

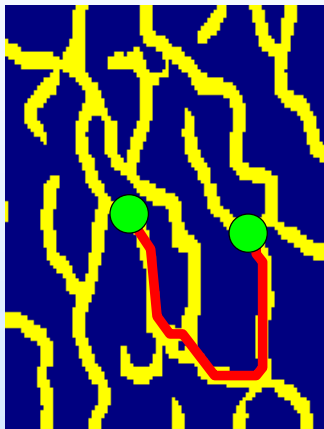


Probability map for CO<sub>2</sub> migration based on the models of the final cluster.

# Technical Status

## An Alternative Connectivity based Proxy

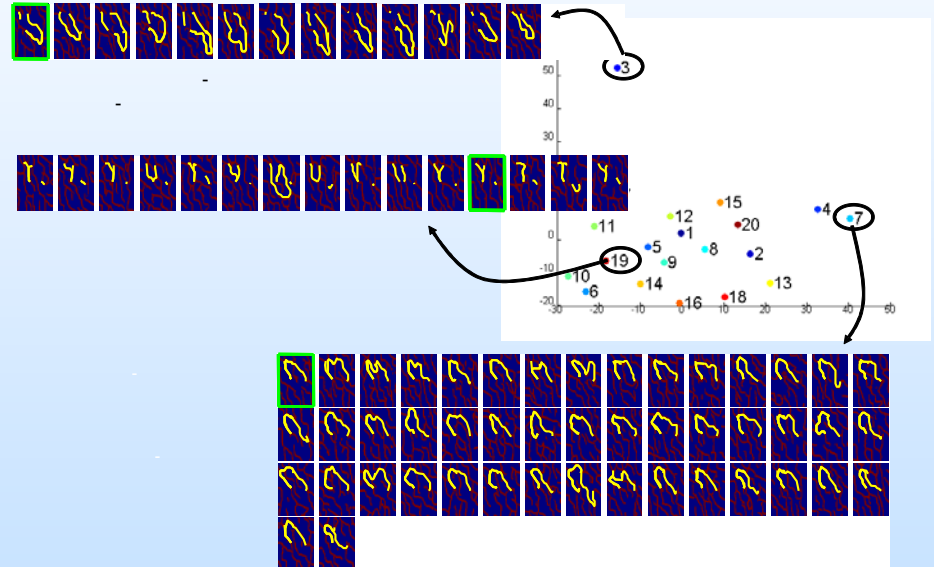
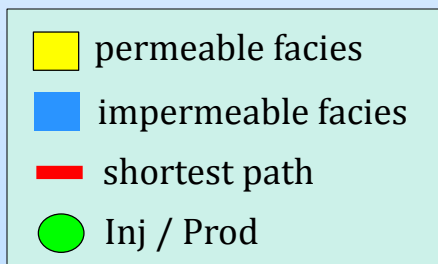
- Fast statistical proxy based on shortest connected path between well locations



Path A1 of model #1



Path A2 of model #2

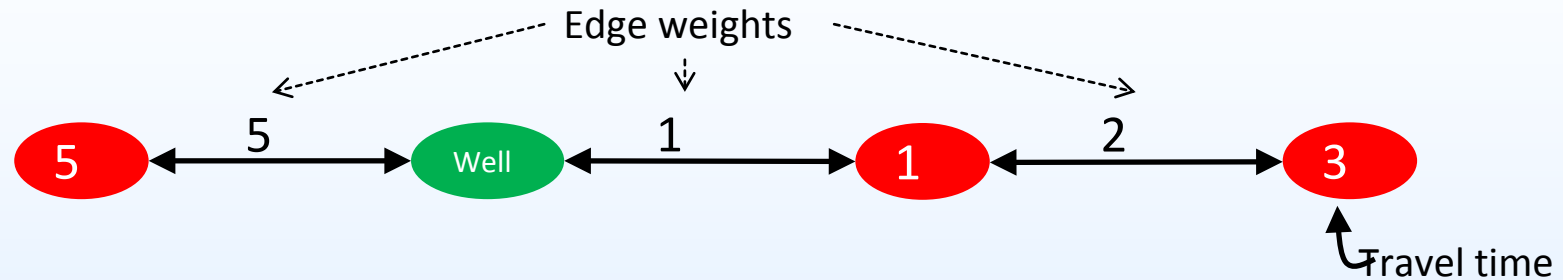


Models exhibit an orderly transition in connectivity characteristics when projected on a metric space

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

# Connectivity Analysis of Models

- Connectivity analysis



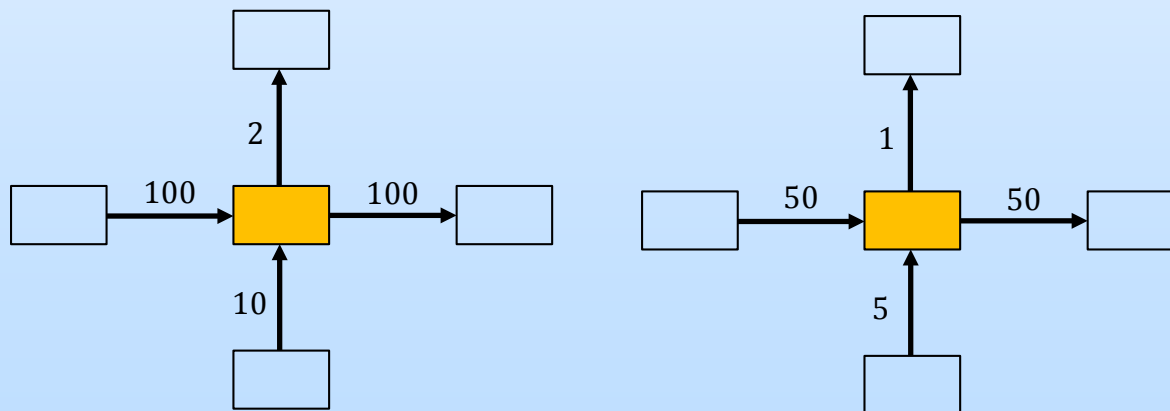
- Measure a connectivity between a well and grid blocks
- $Edge\ weight = \frac{\sqrt{Vp_i \times Vp_j}}{T_{ij}}$ ,  $V_p$ : pore volume,  $T$ : transmissibility
  - travel time of 1 unit viscosity fluid between  $i^{th}$  and  $j^{th}$  grid blocks under 1 unit pressure
- Calculate the shortest paths 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

# Modified Connectivity Analysis

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

$$EdgeWeight = \frac{\sqrt{V_{P_i} \cdot V_{P_j}}}{T_{ij} \cdot \Delta\Phi \cdot \mu_{CO_2}} \quad \Delta\Phi = \Delta P + \Delta\rho gh$$

- Calculate rough  $\Delta P$  from the analytical solution for  $CO_2$  injection in a brine aquifer presented by Manthias *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

## Proxy Verification

Inject CO<sub>2</sub> 10,000 m<sup>3</sup>/day during 2 years

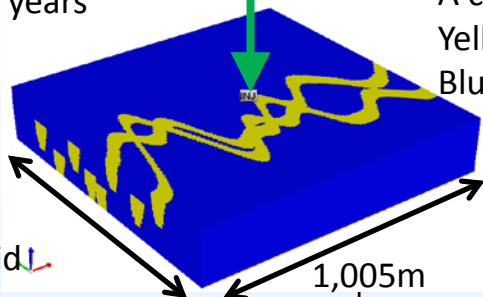
A channel reservoir

Yellow: sand, 300md,  $\phi$  0.2

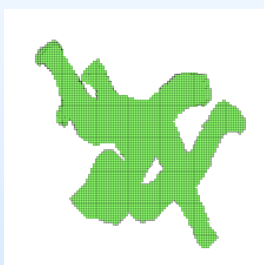
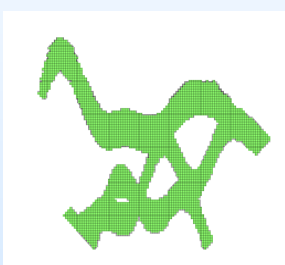
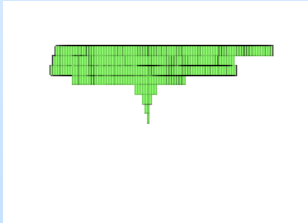
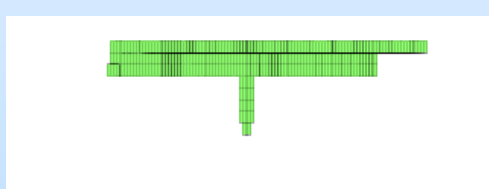
Blue: shale, 1md,  $\phi$  0.1

↕ 20m (10 grid blocks)

1,005m  
(201 grid blocks)



1,005m  
(201 grid blocks)

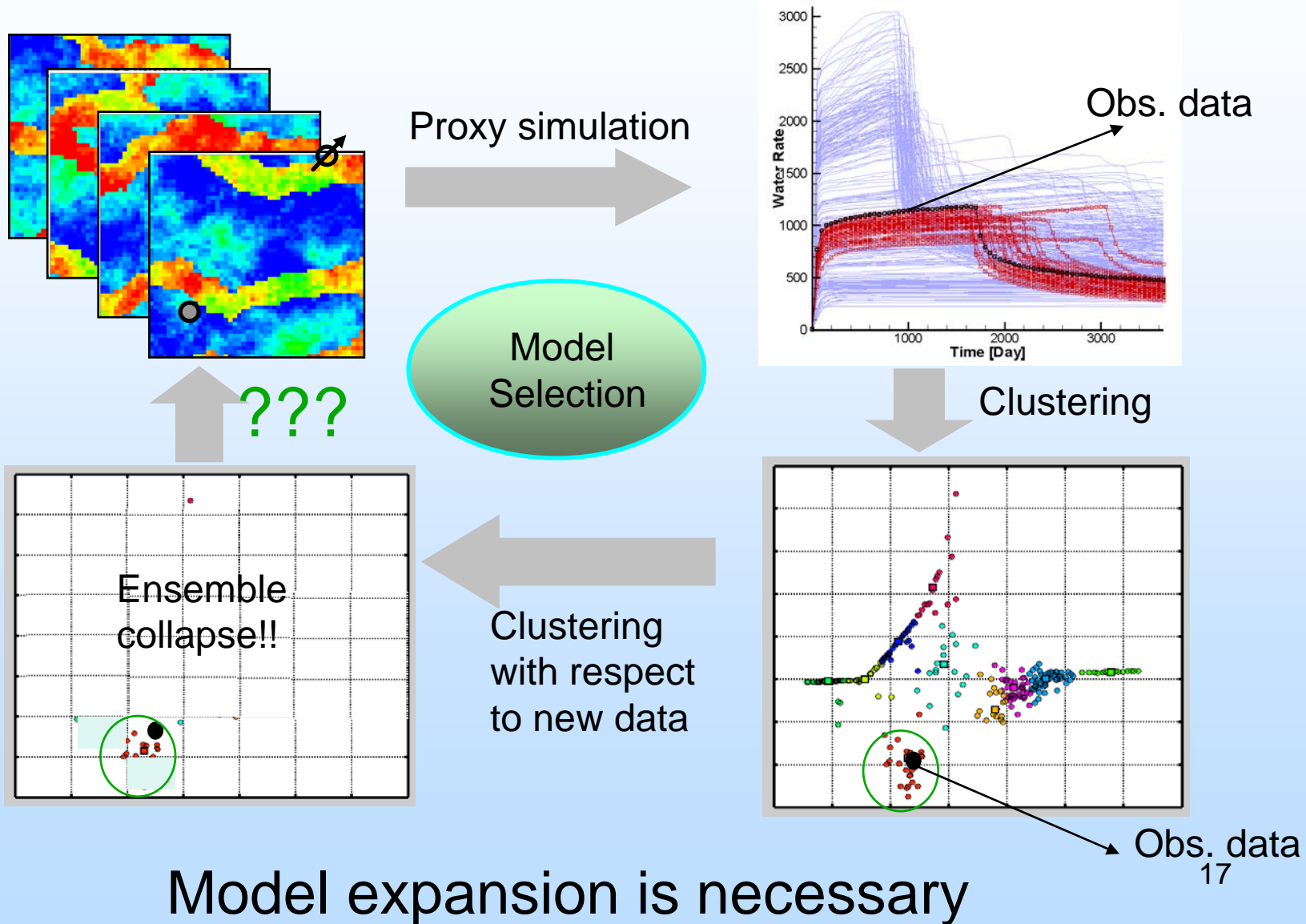
	Migration path by CMG	Path using proxy
Top view		
Side view		
Computation time	1254 sec using 6 processors	4.33 sec using 1 processor

**Our proxy is 300 times faster than the simulator in this case**

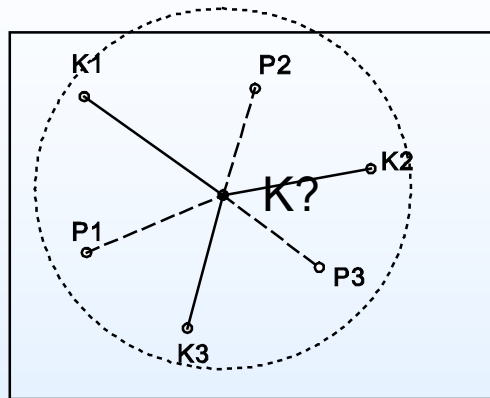


# Technical Status

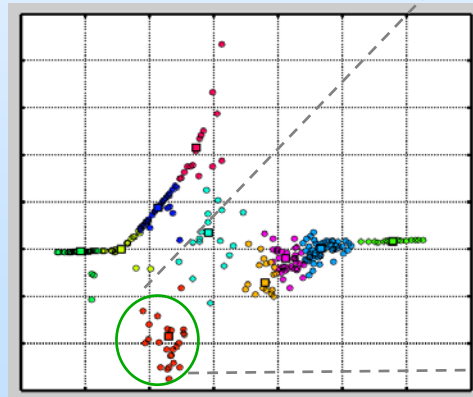
## Model Expansion



# Ensemble-based pattern search

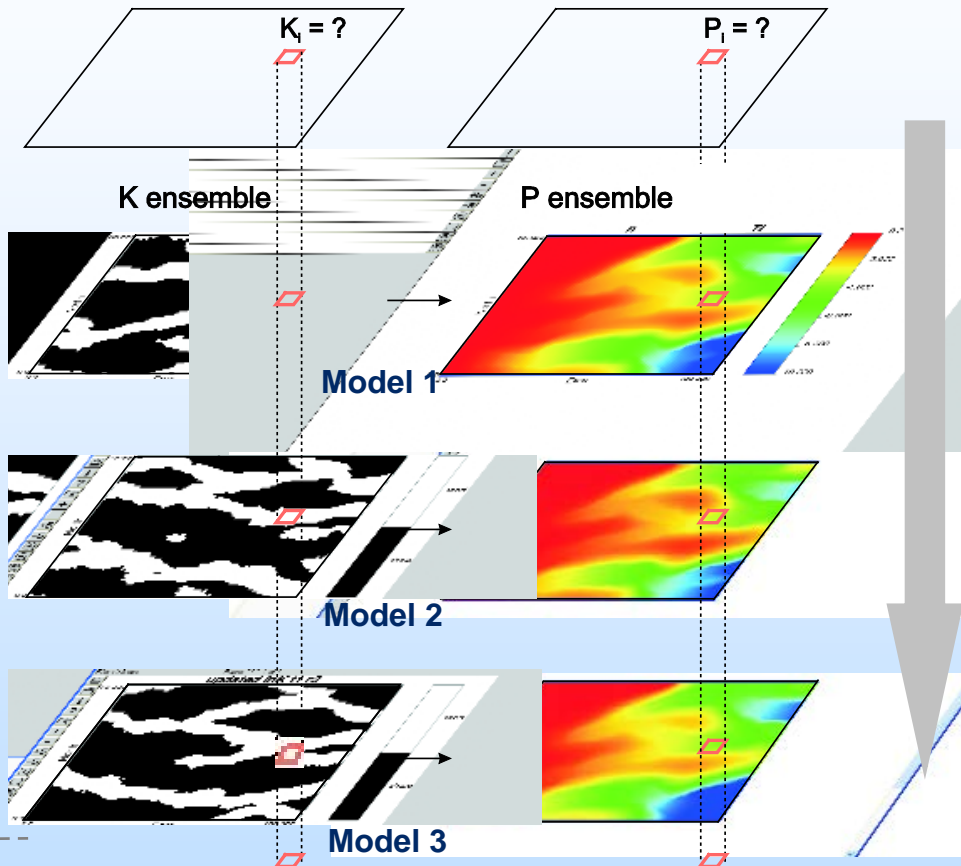


Conditional Pattern



Reservoir Models in Identified Cluster

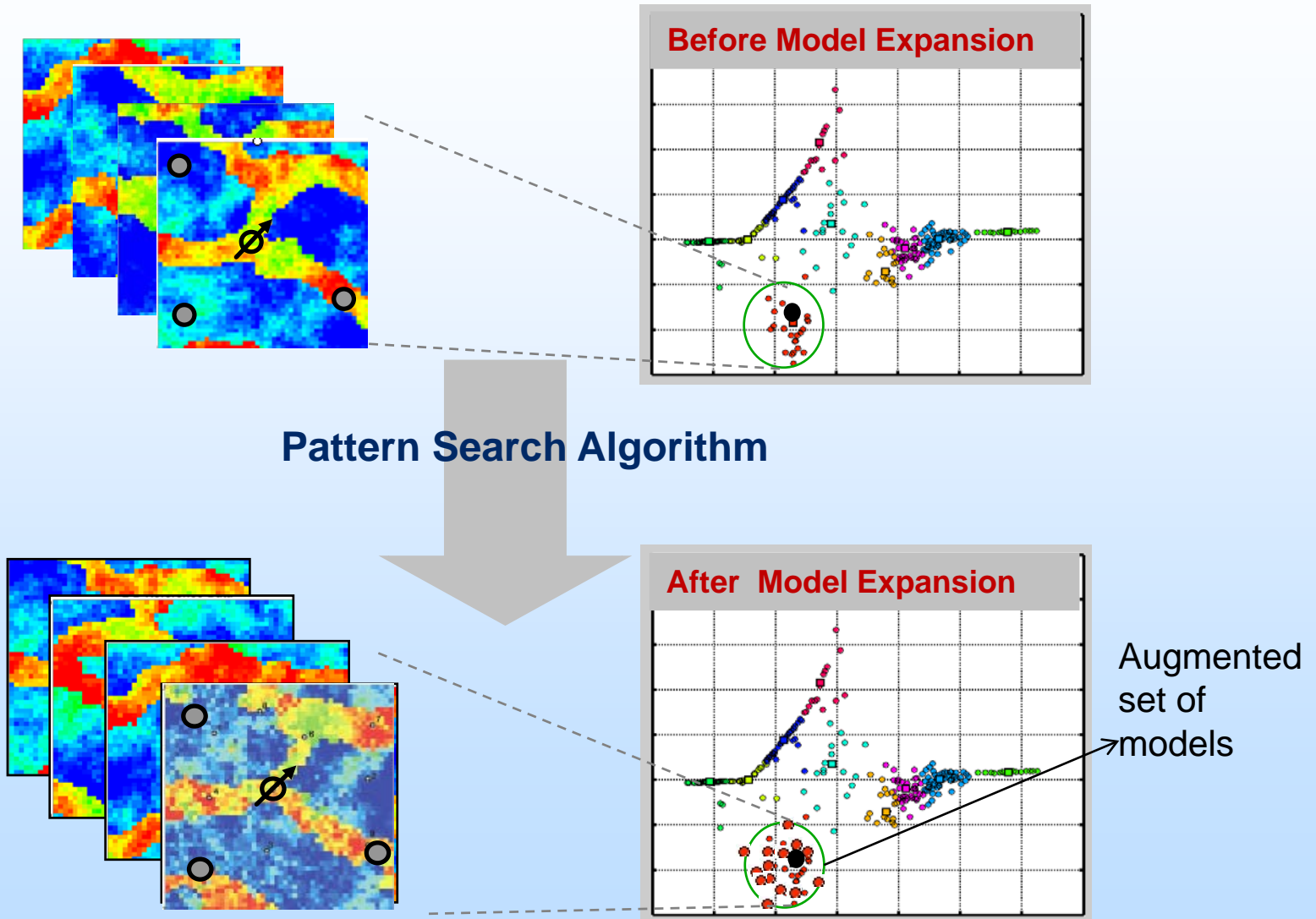
Corresponding Flow Response



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

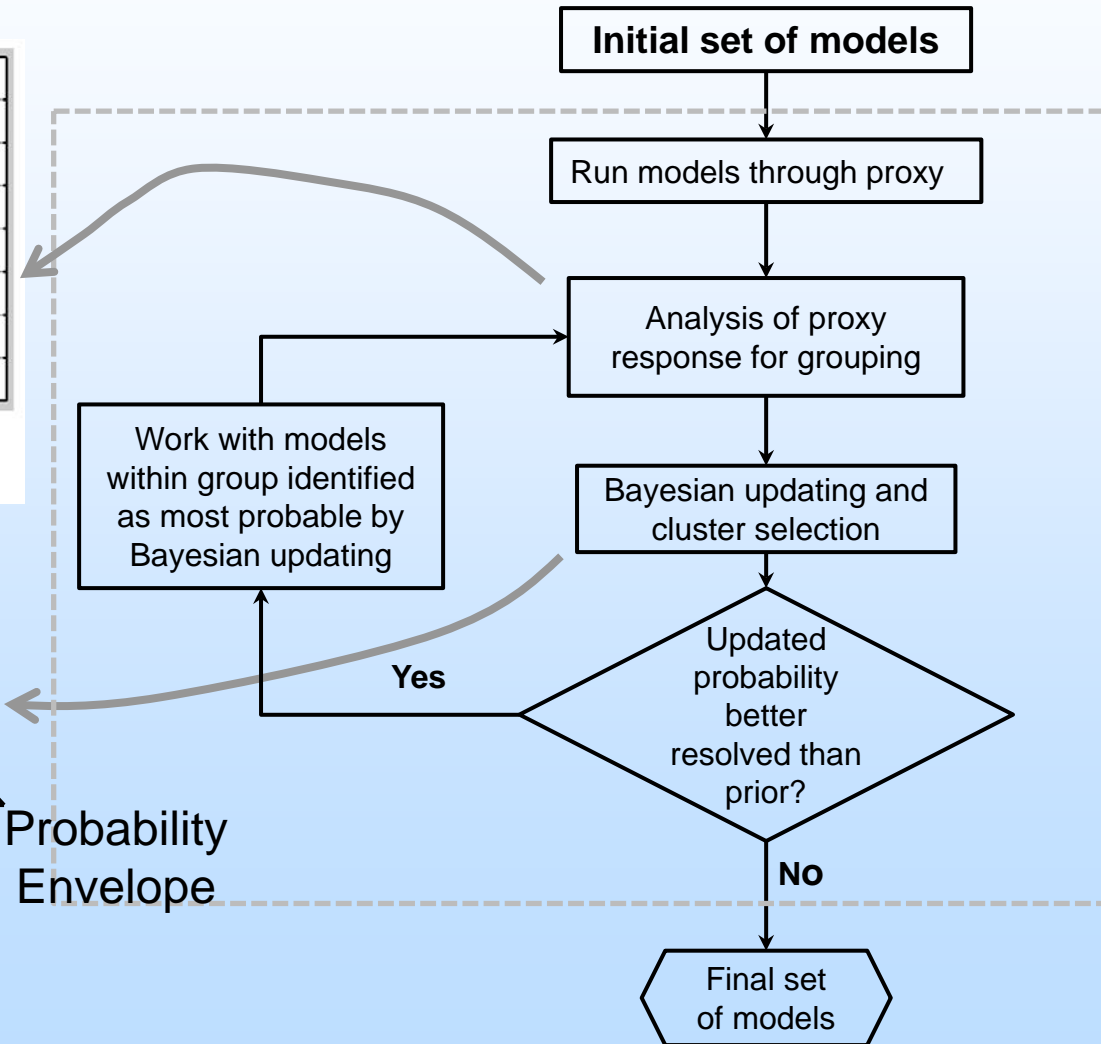
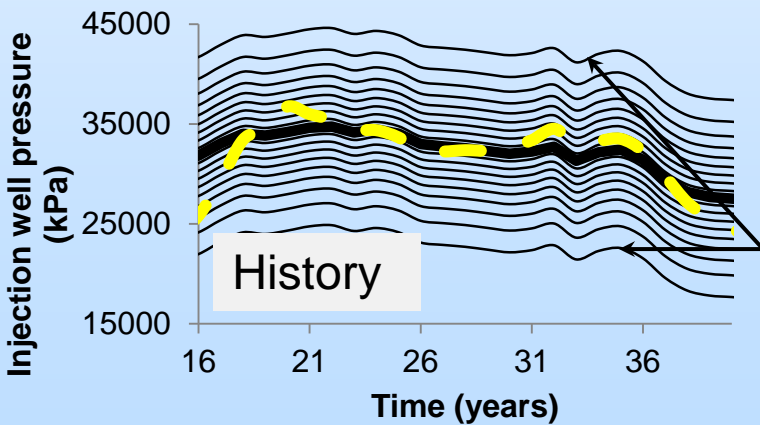
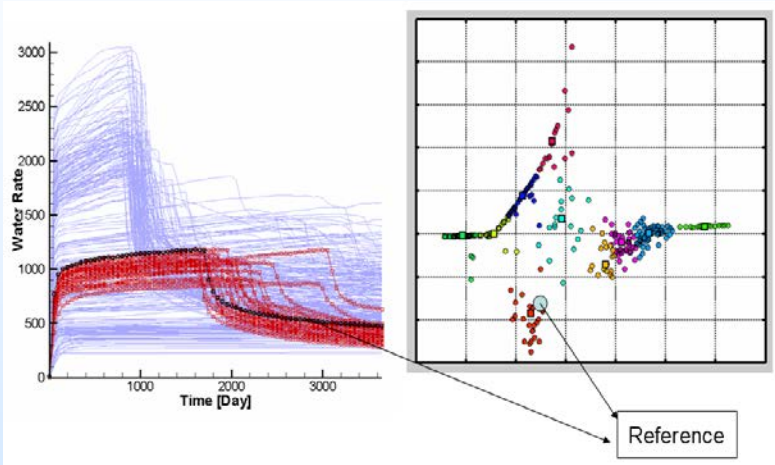
# Technical Status

## Ensemble-based pattern search



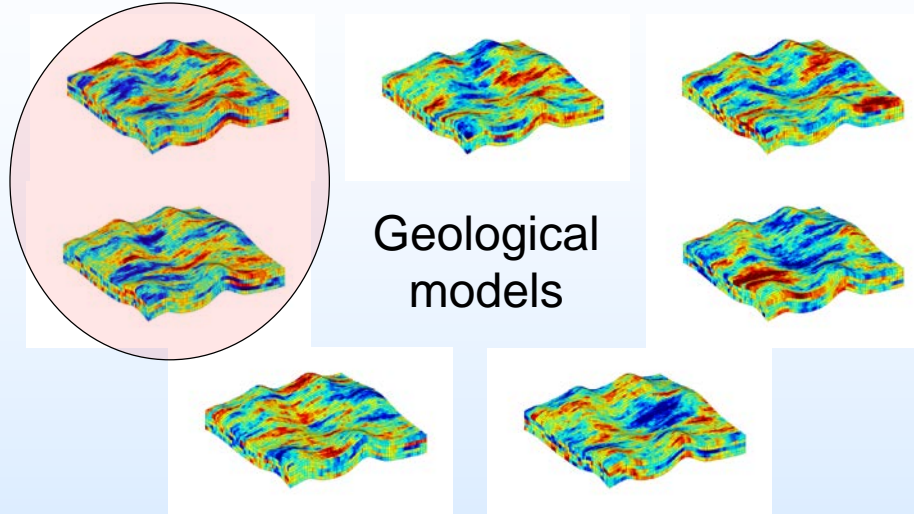
# Technical Status

Integrated, modular software



# Modular Software

A set of the most probable models



- Key objective
  - To select a set of the most probable models honoring injection data among geological models
- Software requirements
  - Separation between generating geological models and selecting in the software requires a complicated importing process
  - Allow to access geologic models directly and to develop additional modules
- SGeMS
  - A powerful freeware providing most of geological modeling algorithms
  - A new algorithm can be added as a plugin

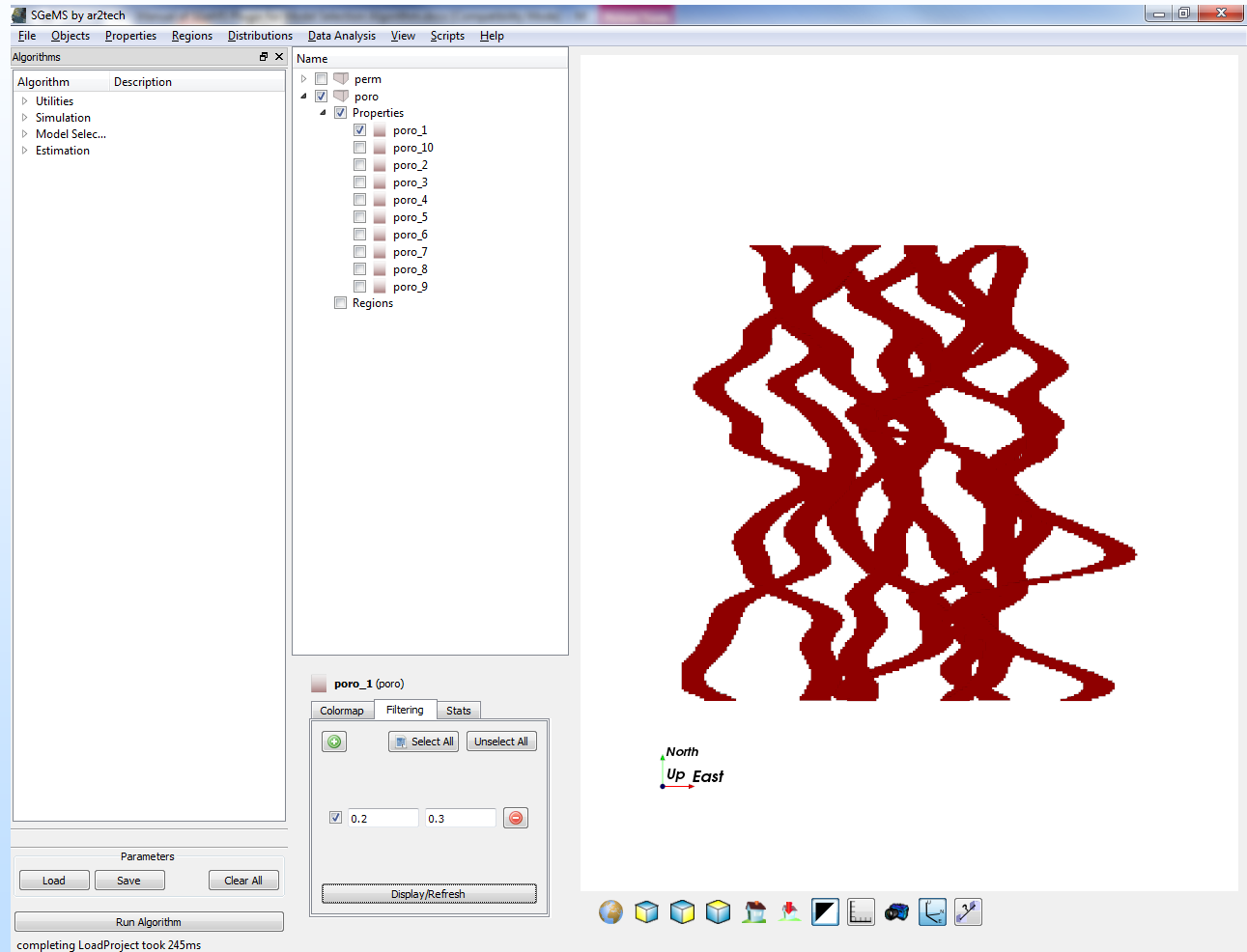
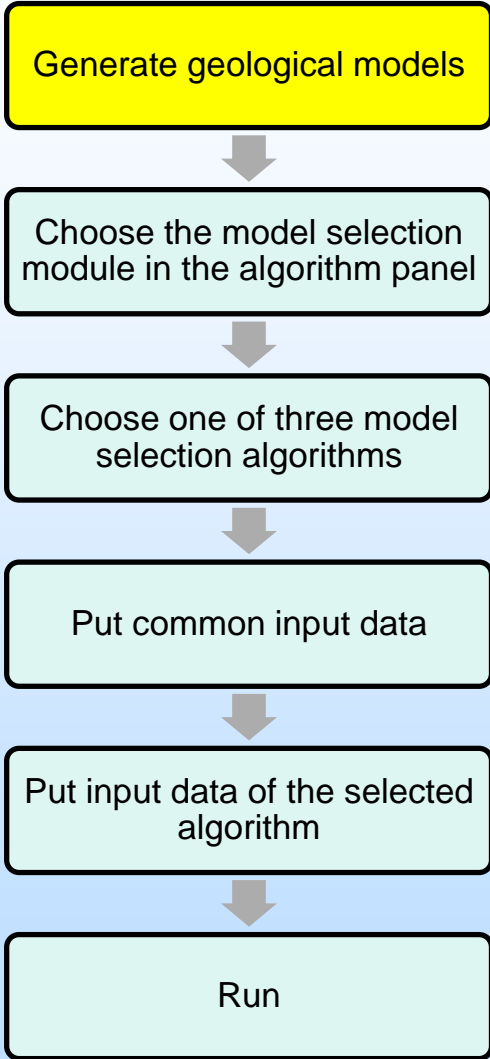
# SGeMS Interface

The screenshot shows the SGeMS software interface with the following components and highlighted panels:

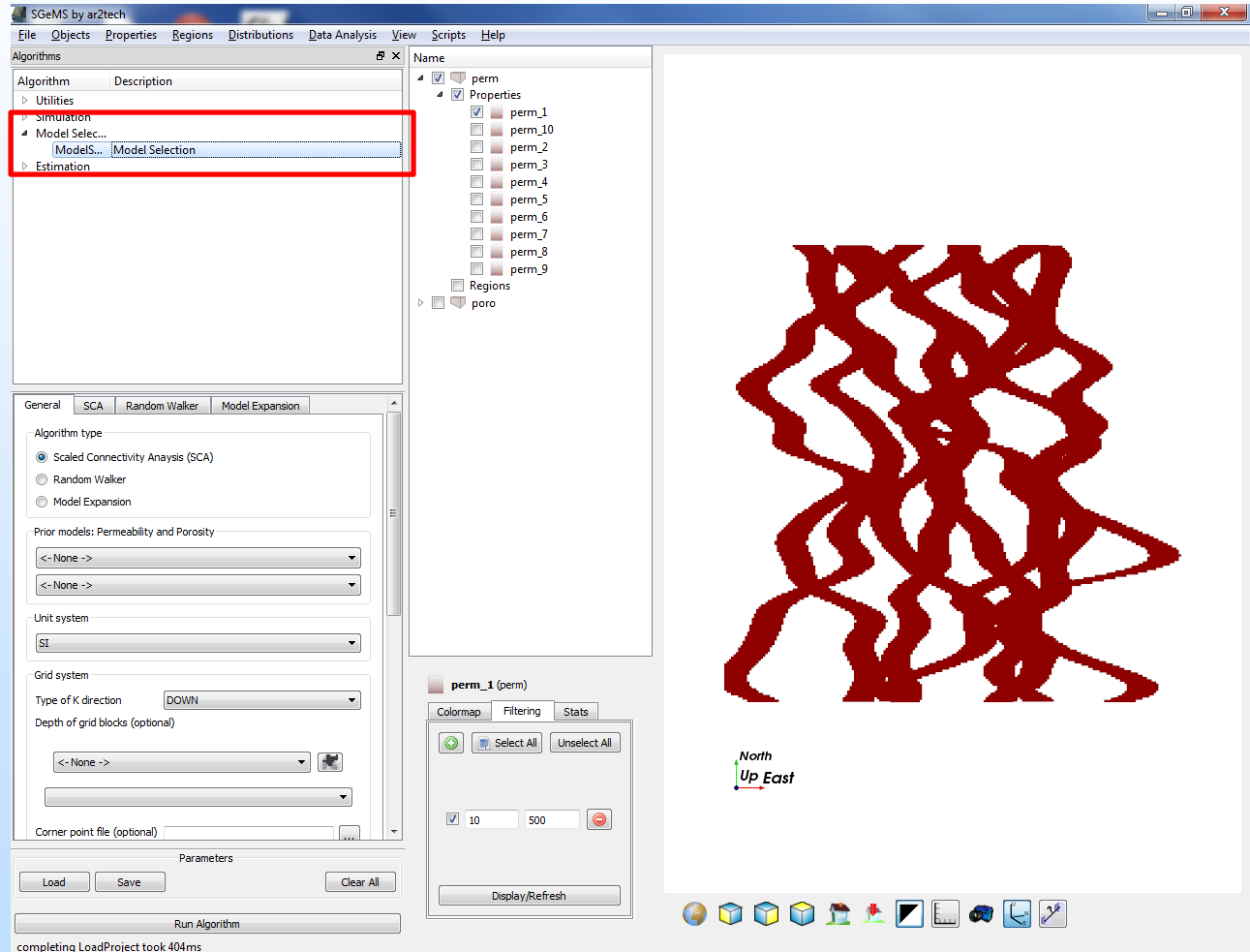
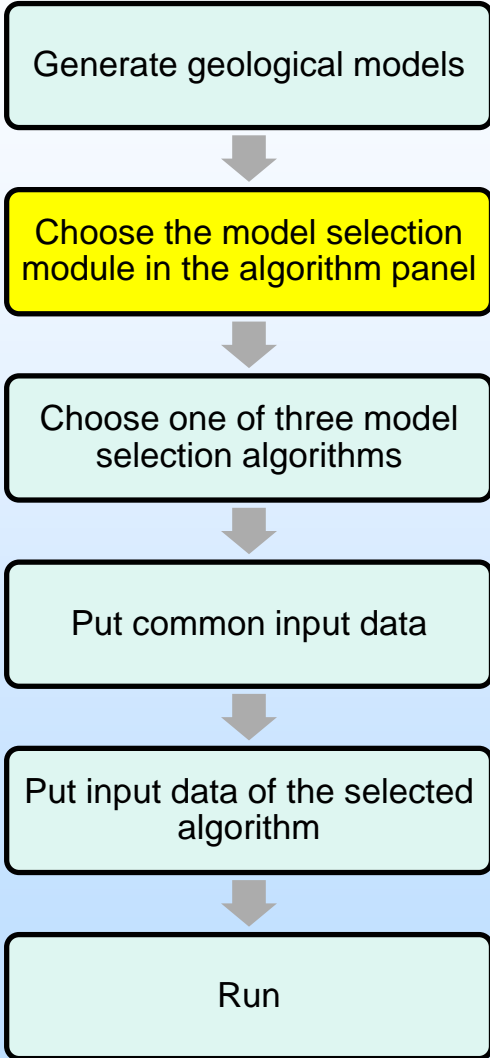
- ALGORITHM PANEL:** Located in the top-left pane, it displays a list of algorithms under the 'Model Selection' category.
- OBJECT PANEL:** Located in the top-right pane, it shows a hierarchical tree of objects including 'perm' (with sub-objects perm\_1 through perm\_9), 'Regions', and 'poro'.
- ALGORITHM INPUT PANEL:** Located in the bottom-left pane, it contains configuration options for the 'Scaled Connectivity Analysis (SCA)' algorithm, such as 'Prior models', 'Unit system', and 'Grid system'.
- VISUALIZATION PANEL:** Located in the large right-hand area, it displays a 3D visualization of a red, interconnected porous structure. Below the visualization is a 'perm\_1 (perm)' control panel with buttons for 'Colormap', 'Filtering', 'Stats', 'Select All', and 'Unselect All'. A 'Display/Refresh' button is also present at the bottom of this panel.

At the bottom of the window, a status bar indicates 'completing LoadProject took 404ms'.

# Procedure for Running the Model Selection Plugin



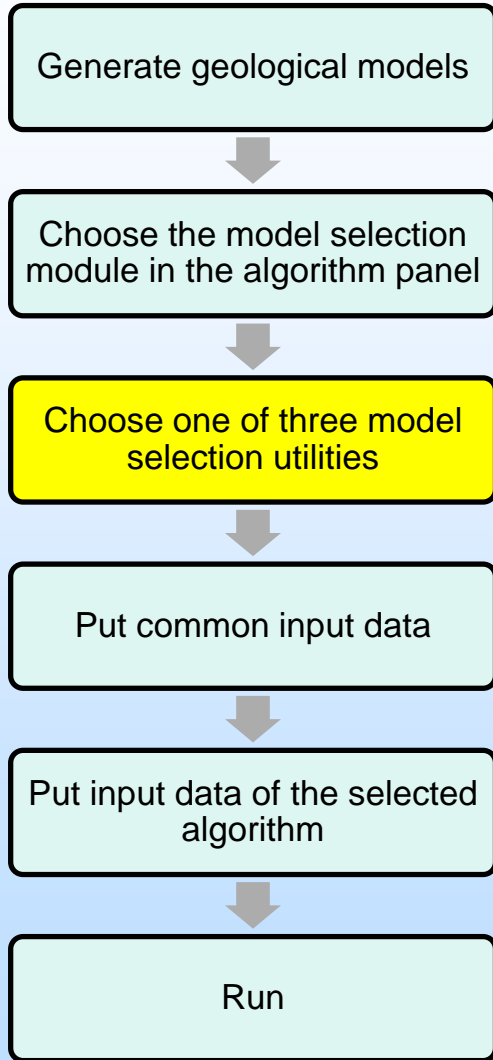
# Procedure of Running the Model Selection Plugin





# Procedure of Running the Model Selection Plugin

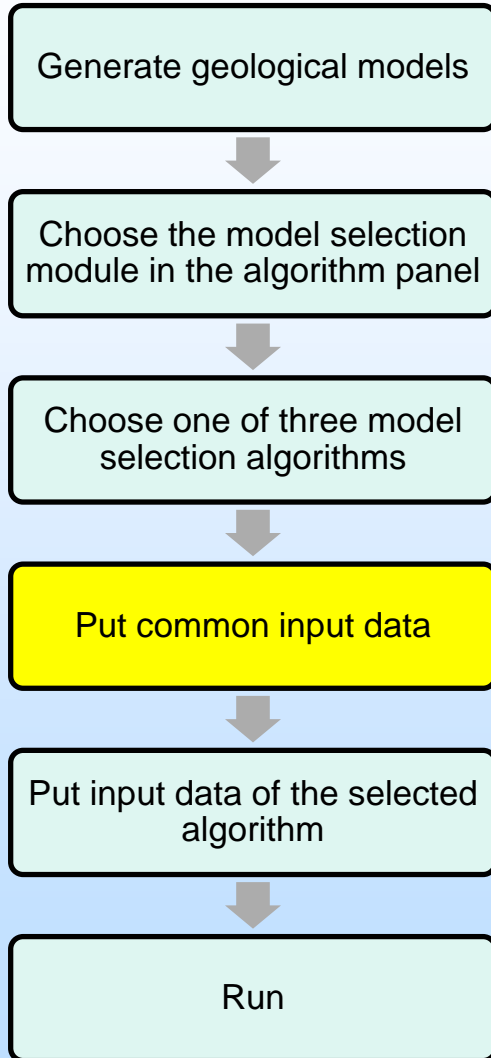
## Algorithm input panel



The screenshot shows the 'Algorithm input panel' for the 'Model Selection Plugin'. The panel is divided into several sections, each with a tab at the top: 'General', 'SCA', 'Random Walker', and 'Model Expansion'. The 'SCA' tab is selected. The 'Algorithm type' section is highlighted with a red box and contains three radio buttons: 'Scaled Connectivity Analysis (SCA)' (selected), 'Random Walker', and 'Model Expansion'. Below this, the 'Prior models: Permeability and Porosity' section has two dropdown menus, both set to '<- None ->'. The 'Unit system' section has a dropdown menu set to 'SI'. The 'Grid system' section has a 'Type of K direction' dropdown set to 'DOWN' and a 'Depth of grid blocks (optional)' dropdown set to '<- None ->'. The 'Corner point file (optional)' field is empty. The 'Simulation' section contains several input fields: 'Observation file', 'Observation type' (set to 'Well data'), 'Simulator input file', 'Perm include file name', 'Poro include file name', 'Simulator file', 'CMG simulator command' (with a default command), 'Report input file', '# of header lines in report output', 'Report file', and 'CMG report command' (with a default command). Each input field has a corresponding number in brackets next to it, ranging from [1] to [18].

# Procedure of Running the Model Selection Plugin

## Algorithm input panel



The screenshot shows the 'Algorithm input panel' with the following sections and numbered callouts:

- Algorithm type:** Radio buttons for Scaled Connectivity Analysis (SCA) [1], Random Walker, and Model Expansion.
- Prior models: Permeability and Porosity:** Two dropdown menus, both set to '<- None ->' [2] and [3].
- Unit system:** A dropdown menu set to 'SI' [4].
- Grid system:** A dropdown menu set to 'DOWN' [5]. Below it, a field for 'Depth of grid blocks (optional)' is set to '<- None ->' [6].
- Simulation:** A section containing several input fields: 'Observation file' [8], 'Observation type' set to 'Well data' [9], 'Simulator input file' [10], 'Perm include file name' [11], 'Poro include file name' [12], 'Simulator file' [13], 'CMG simulator command' [14] (with a command line below it), 'Report input file' [15], '# of header lines in report output' [16], 'Report file' [17], and 'CMG report command' [18] (with a command line below it).

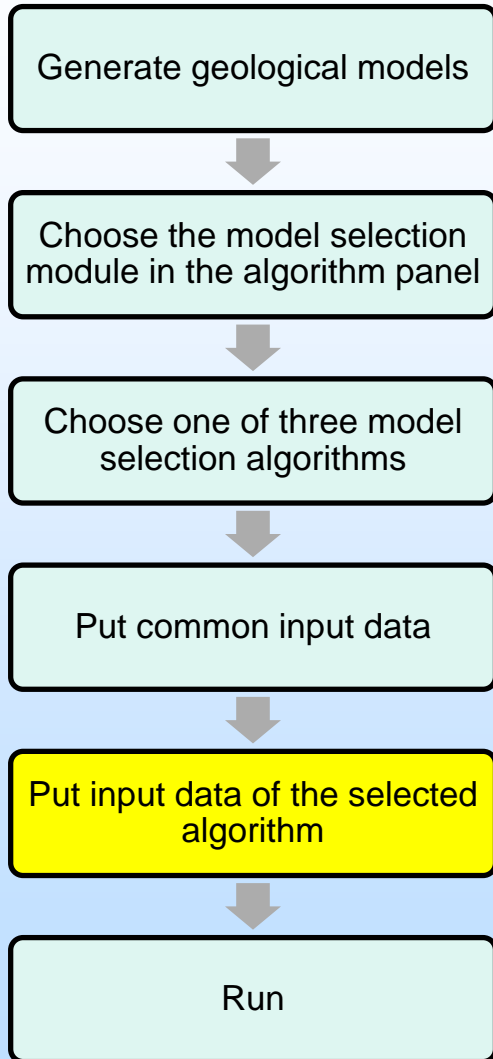
Choose prior models for permeability and porosity

Choose a unit system

Choose a grid system (ex: K direction)

Provide observation data and information to run a simulator and read simulation results

# Procedure of Running the Model Selection Plugin

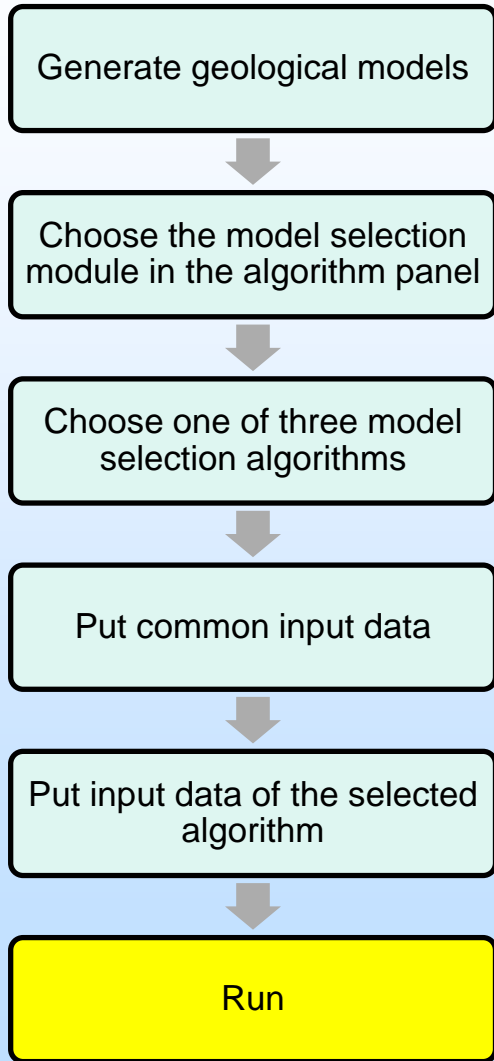


## Input data of SCA

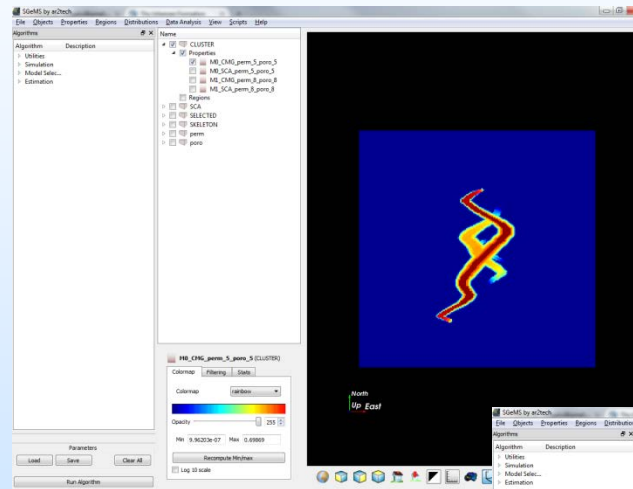
The screenshot shows a software interface with four tabs: 'General', 'SCA', 'Random Walker', and 'Model expansion'. The 'SCA' tab is active. The form is divided into several sections:

- Operating conditions:**
  - CO2 volume in SC / CO2 volume in RC: 0.004147892
  - Injection period (yrs): 2
  - Injection flow rate in SC (m3/day): 10000
  - Injector location(i j k): 100, 100, 7
- Fluid properties in reservoir condition:**
  - CO2 viscosity (cp): 0.036
  - CO2 density (kg/m3): 443
  - Water density (kg/m3): 1007
- SCA parameters:**
  - Average CO2 saturation: 0.5
  - Down dip angle limit (degrees): 5
  - CO2 relative perm at Avg. CO2 Saturation: 0.2932
  - Reservoir thickness (m): 20
  - Power averaging for permeability: 0
  - 1=harmonic, 0=geometric, 1=arithmetic
- Clustering parameters:**
  - Number of clusters (Optional):

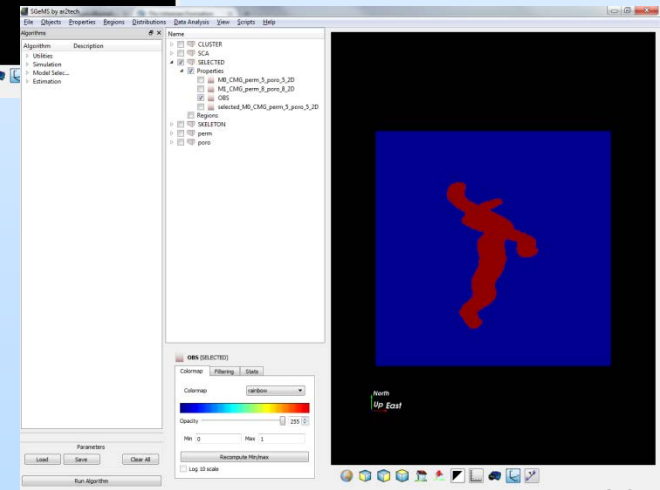
# Procedure of Running the Model Selection Plugin



Simulation result of the representative model in the selected group



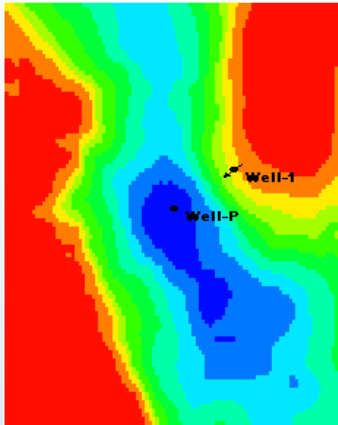
Proxy result of the representative model in the selected group



# Technical Status

## Effect of Unknown Leak on Model selection

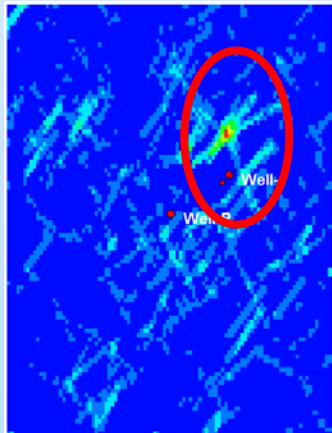
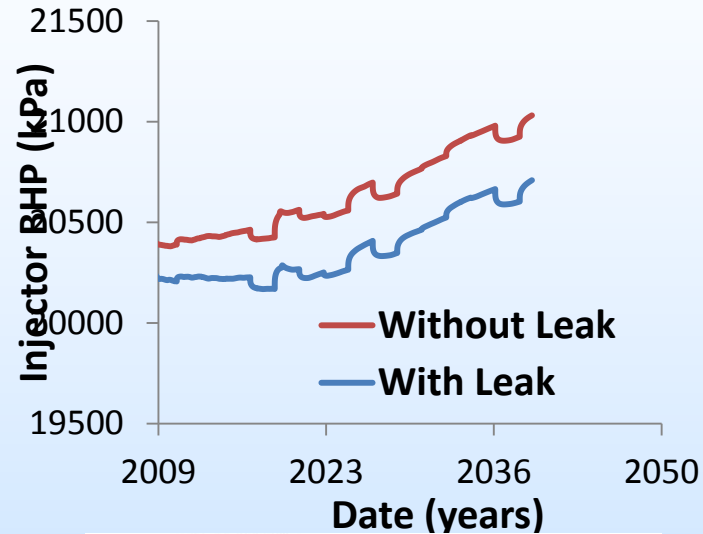
- Reservoir model for the Krechba reservoir (In Salah)



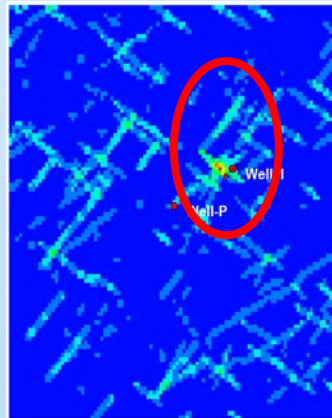
Krechba Reservoir Model



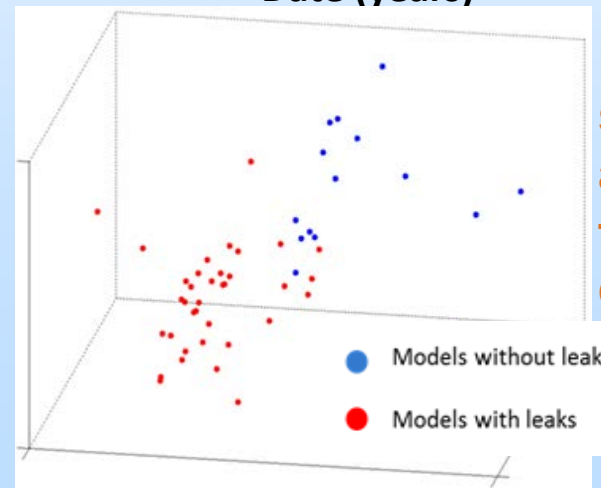
Location of injector, streak and leak



Average model when there is no leak



Average model with leak



Model selected with and without the leak are different

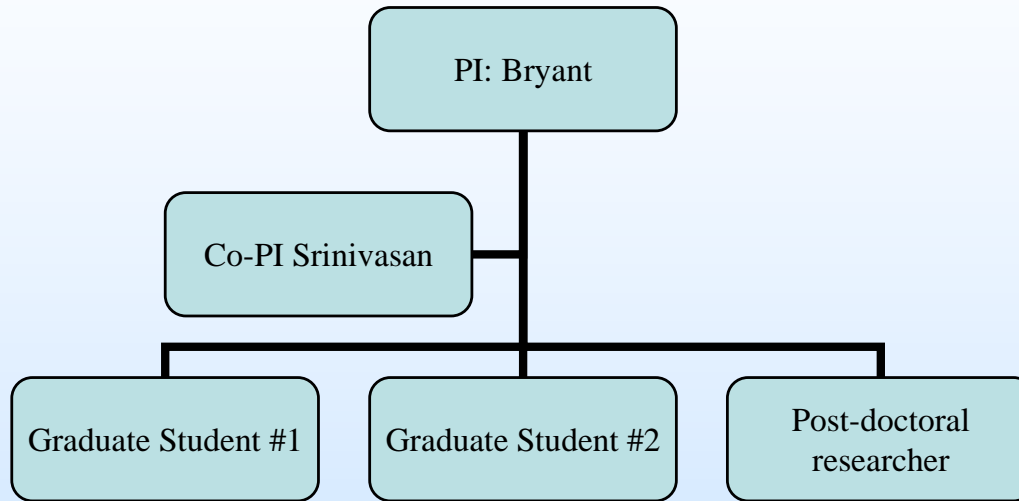
# Accomplishments to Date

- Sensitivity analysis of impact of subsurface heterogeneity on injection response
- Fast model responses
  - Proxy to account for permeability heterogeneity, fluid compressibility, buoyancy effect
  - Statistical proxy using Frechet distance between shortest connected path between wells
- Effective model classification
  - PCA, Kernel PCA, Multi-dimensional scaling methods
- Re-sampling scheme for posterior uncertainty modeling
- Modular software for model selection
  - Beta-testing using student volunteers using synthetic and field datasets

# Summary

- Model Selection Algorithm allows delineation of dominant heterogeneity features that drive fluid migration
- Fast proxies such as particle-tracking proxy and scaled connectivity analysis provide rapid assessment of reservoir / aquifer connectivity
- Modular software able to predict plume movement in In Salah and Utsira/Sleipner
- Model selection procedure sensitive to presence of unresolved leaks and other factors such as boundary conditions
- Model Selection approach is being extended to incorporate information from surface deflection data

# Appendix



- Project has provided training and research experience for two graduate students – Hoonyoung Jeong (current PhD student) and Sayantan Bhowmick (graduates and with Conoco Phillips) and a post-doctoral fellow – Dr. Liangping Li



# Gantt Chart

Phase	Task	Milestone	YEAR 1				YEAR 2				YEAR 3				Interdependencies
			1	2	3	4	1	2	3	4	1	2	3	4	
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														
2	5	2.A								X					Combines Tasks 2-4 into software platform
	6	2.B									X				Validates Task 5
	7														Uses Phases 1, 2 to quantify uncertainty
3	8.1														Uses Phase 2 to apply concept to field data
	8.2	3.A										X			Applies Phase 2 to In Salah
	8.3	3.B												X	Applies Phase 2 to RCSPs
			Phase 1				Phase 2				Phase 3				

# Bibliography

## Journal, multiple authors:

1. Srinivasan, S., and Jeong, H., Modeling the Uncertainty in CO<sub>2</sub> Plume Migration During Sequestration Using a Model Selection Approach. Accepted for publication in special issue of Indian Geophysical Union (IGU), September, 2014.
2. Li, Liangping, Srinivasan, S., Zhou, H. and Gomez-Hernandez, J., “Simultaneous estimation of both geologic and reservoir state variables within an ensemble-based multiple-point statistic framework,” accepted for publication in *Mathematical Geosciences*, September 2013.

## Publication:

1. Jeong, H., Srinivasan, S. and Bryant, S.L., 2012, Uncertainty Quantification of CO<sub>2</sub> Plume Migration Using Static Connectivity, proceedings of International Conference on Greenhouse Gas Technologies (GHGT), Kyoto, Japan.
2. Bhowmick, S., Srinivasan, S. and Bryant, S.L., 2012, Prediction of Plume Migration Using Injection Data and a Model Selection Approach, proceedings of International Conference on Greenhouse Gas Technologies (GHGT), Kyoto, Japan.