Inexpensive Monitoring and Uncertainty Assessment of CO_2 Plume Migration

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Developing the Technologies and
Infrastructure for CCS

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Presentation Outline

- 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_2 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_2 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_2 remains in the injection zones

Project Overview: Success Criteria

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

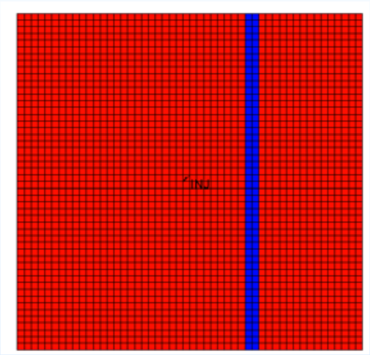
Robust assessment of uncertainty in predicting plume migration path

– Implementation of model resampling to enhance the selection of models within a selected cluster so that the problem of model collapse is avoided

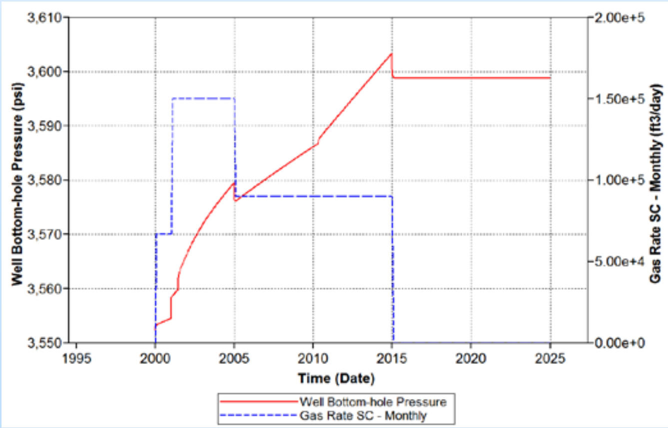
– Deployment of a modular software for plume monitoring that could be integrated with existing tools and frameworks for risk assessment

Technical Status

Assessment of heterogeneities with detectable signatures



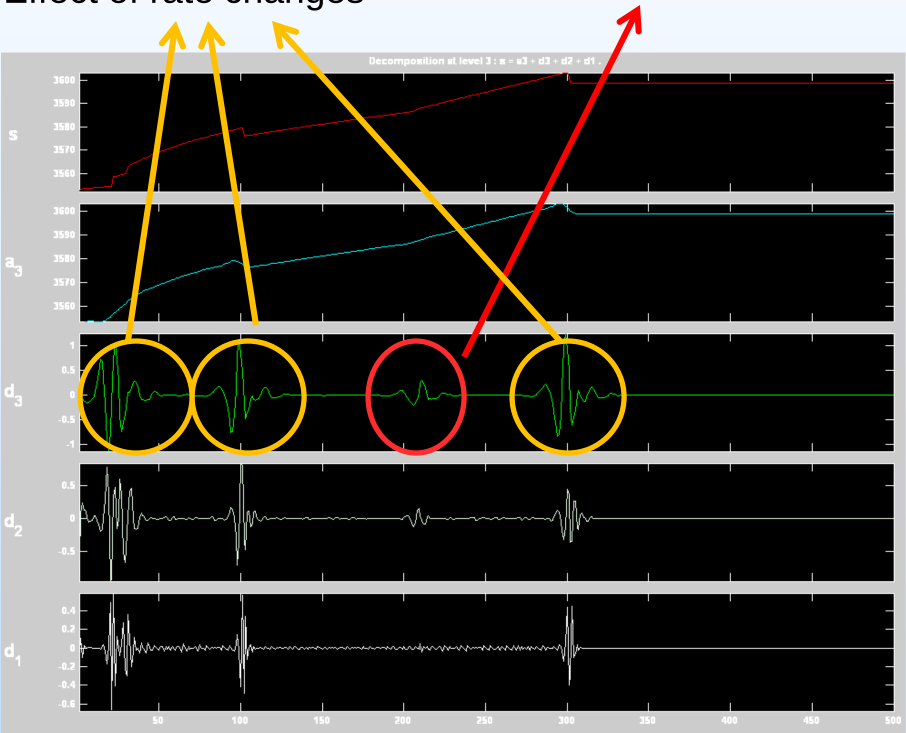
Permeability Heterogeneity



Rate Fluctuations

Effect of rate changes

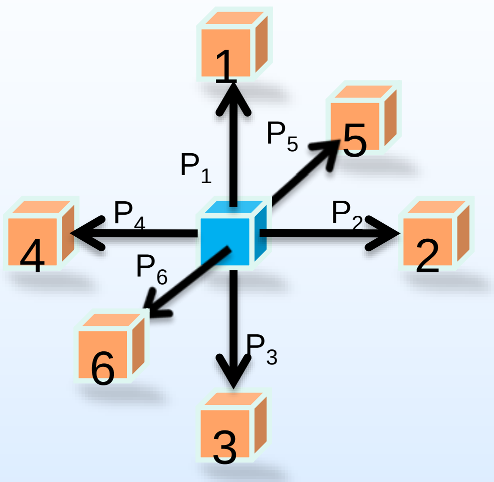
Effect of heterogeneity



Wavelet Analysis using Daubechies wavelet

Technical Status

Development of a physical Proxy and validation cases



Particle Tracking Algorithm

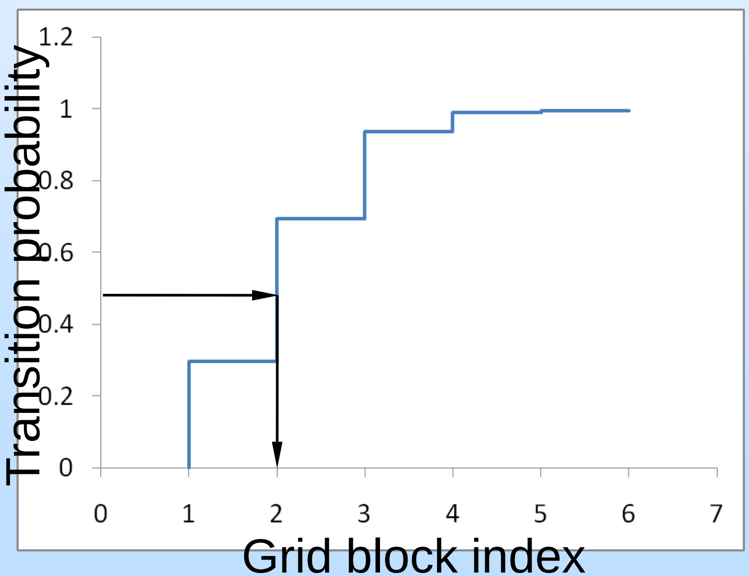
Transition probability

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

where

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

Specific velocity — **Darcy velocity** — **Fractional flow value**



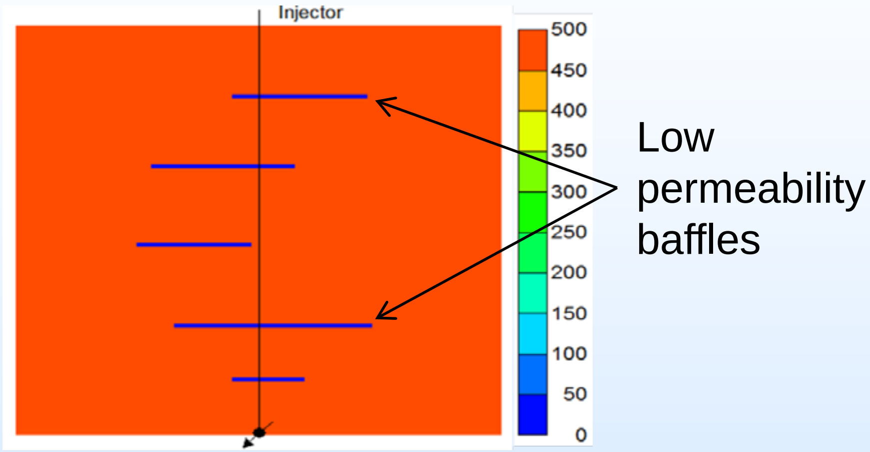
$$v_{macro} = \frac{[\Delta P + \Delta\rho g \Delta z] k_{avg,i\rightarrow j}}{\mu_{CO_2} L} \qquad \Delta P = \frac{qB\mu}{4\pi k_{avg,path} L_{path}} \mathrm{erfc}\left(\sqrt{\frac{\phi \mu c_t L_{path}^2}{4 k_{avg,path} t}}\right)$$

Raghavan 1993

Technical Status

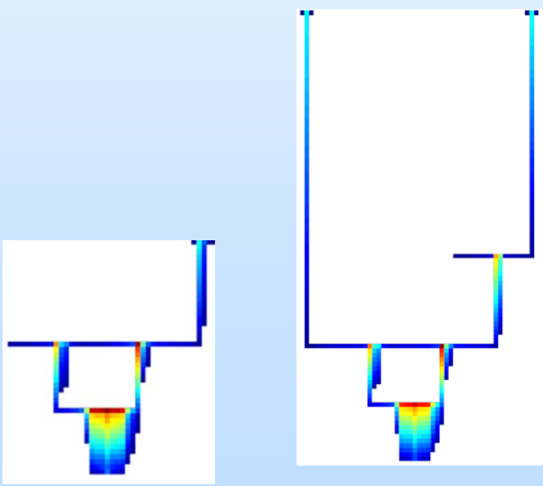
Proxy Verification

PERMEABILITY



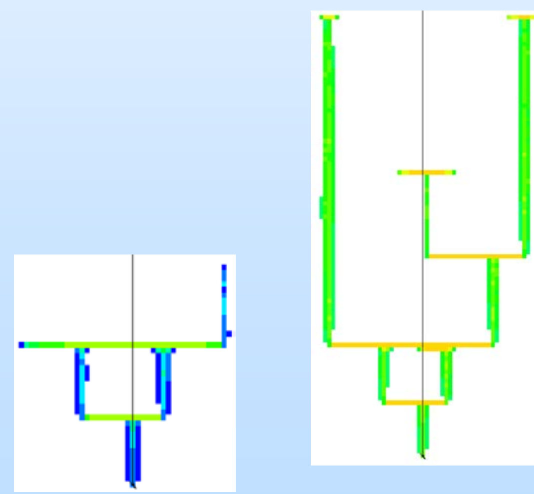
SYNTHETIC MODEL:

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



800 days **2000 days**

Proxy result



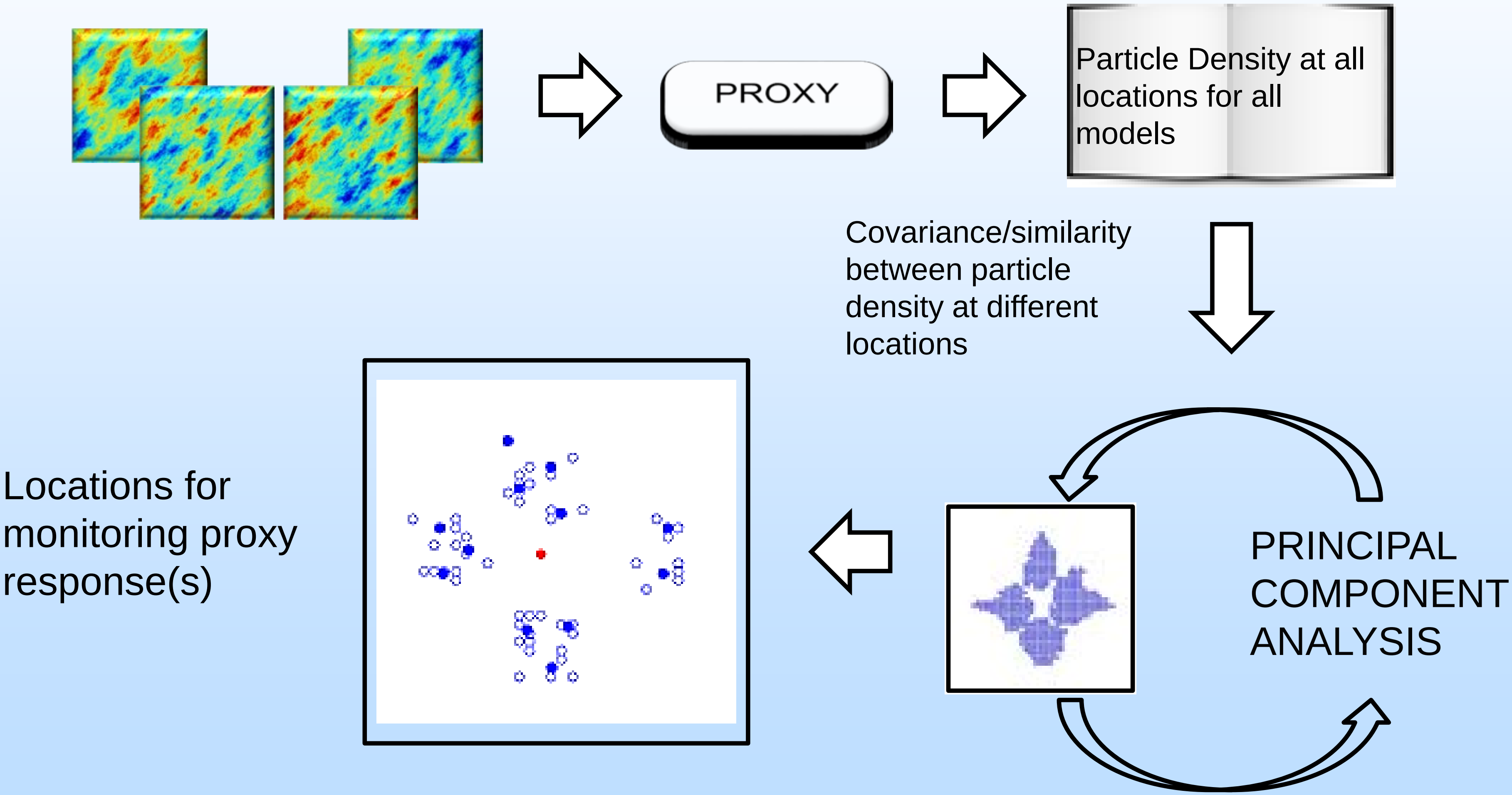
800 days **2000 days**

Numerical simulation result

Technical Status

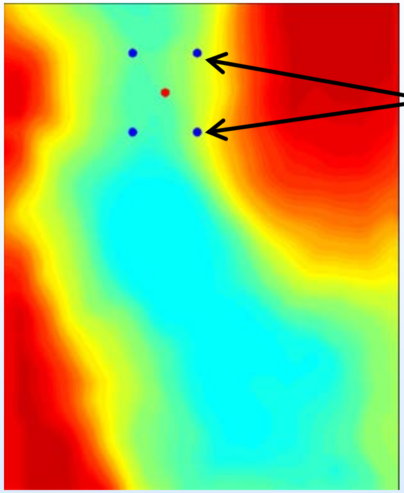
Proxy Measurement locations

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

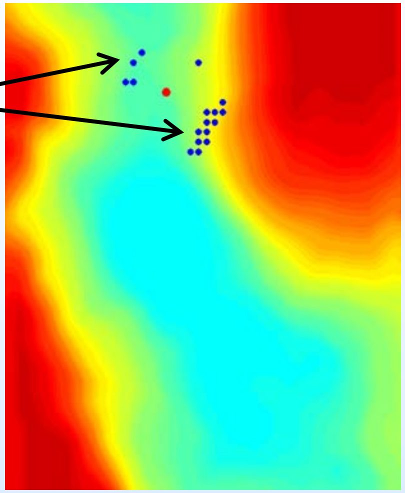


Optimizing proxy monitoring locations

- Monitoring locations using new method for Krechba

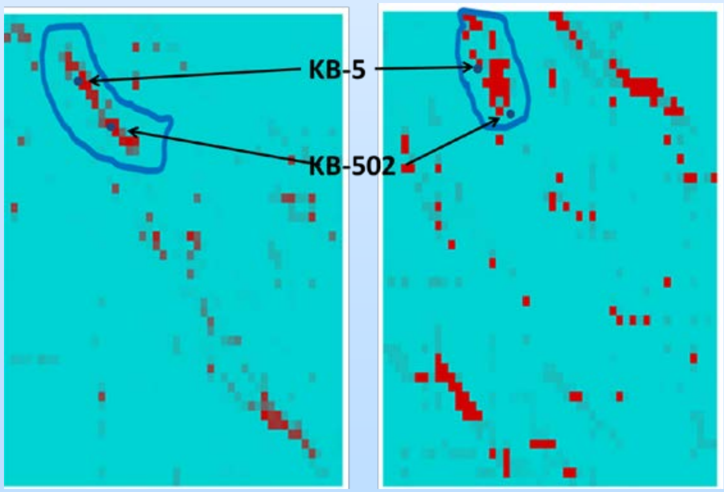


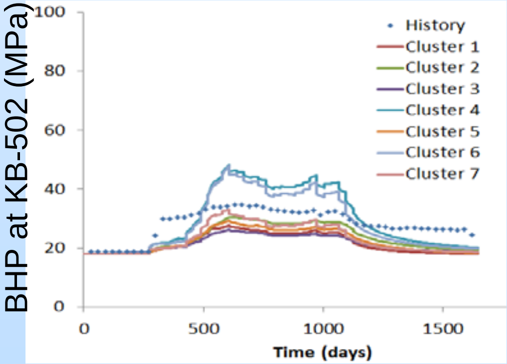
Proxy response measurement locations

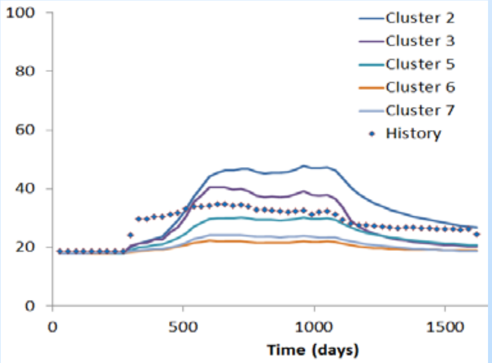


Monitoring locations on a square template

Monitoring locations using PCA defined template







Model Selection Results Similar for both cases

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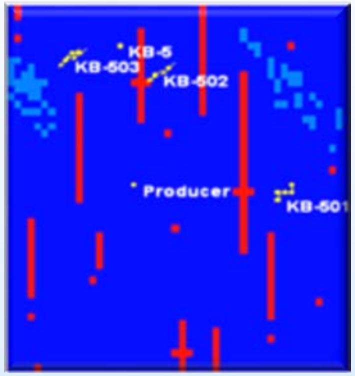
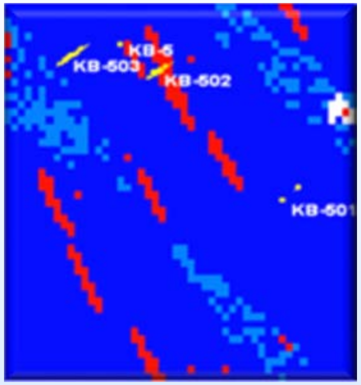
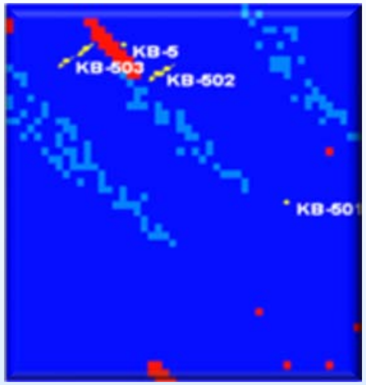
Technical Status

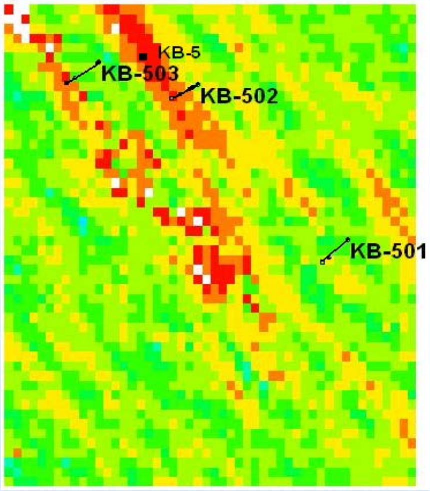
Key Result

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

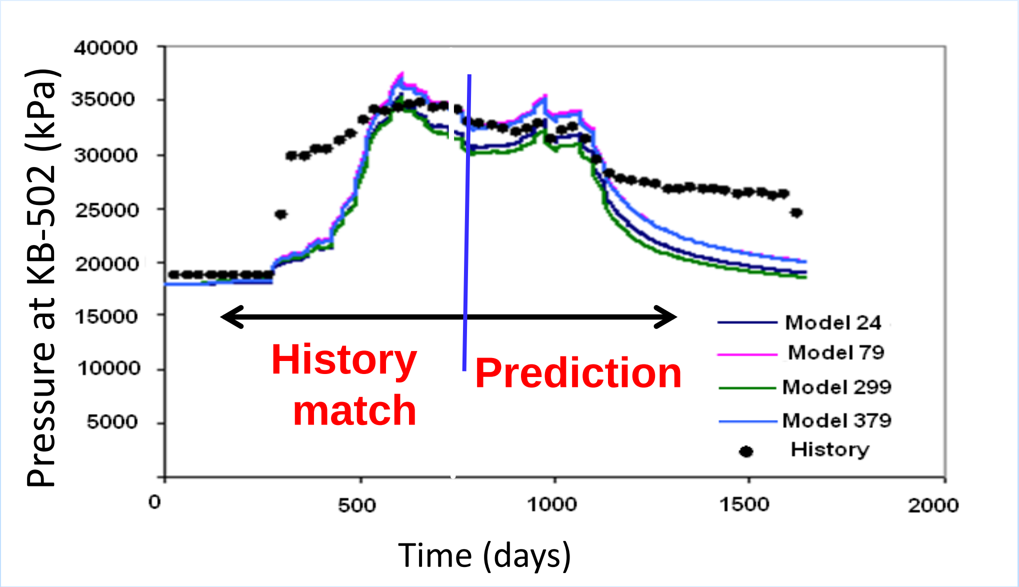






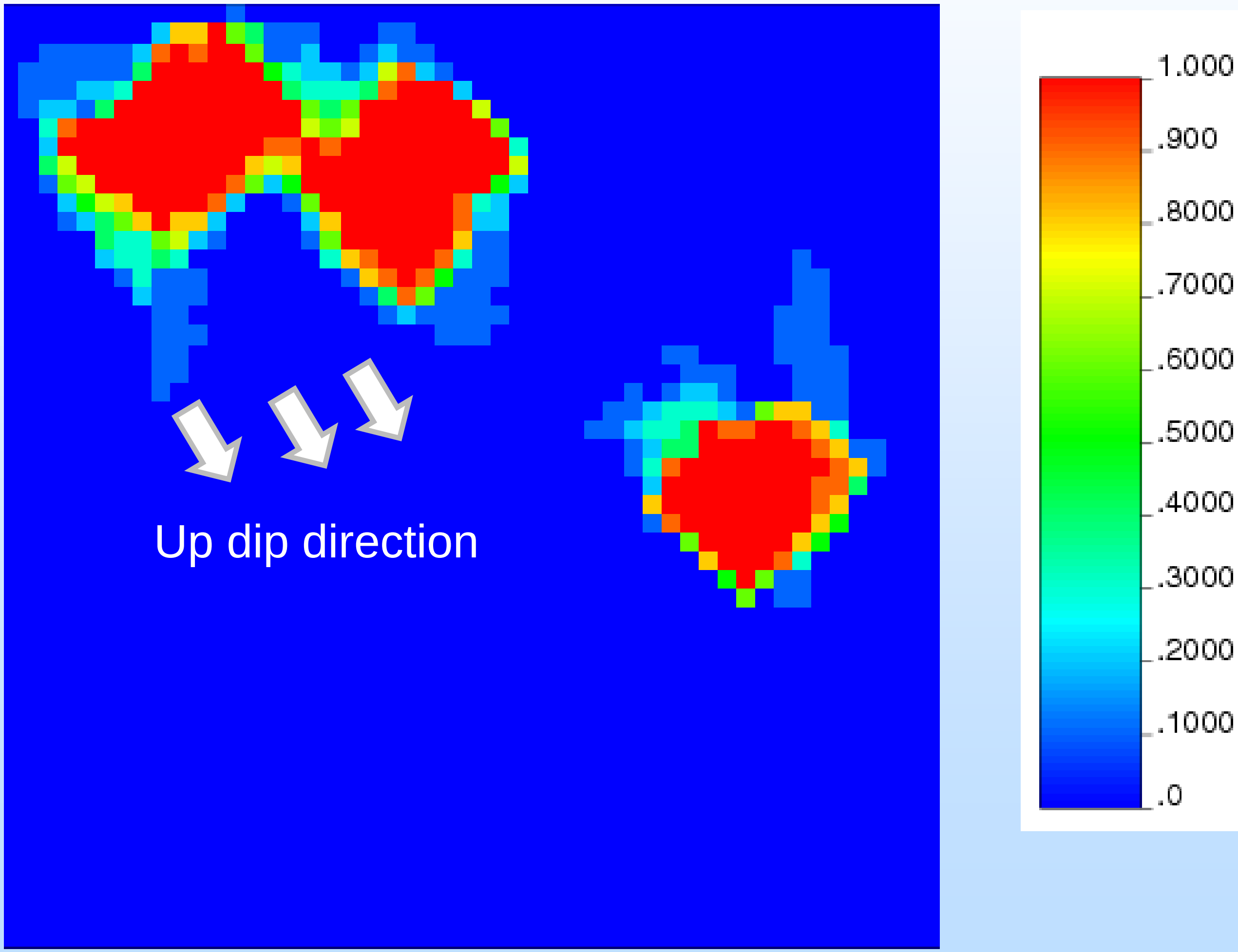


Average of all models from final cluster, showing high permeability streak highlighted over all models



Technical Status

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

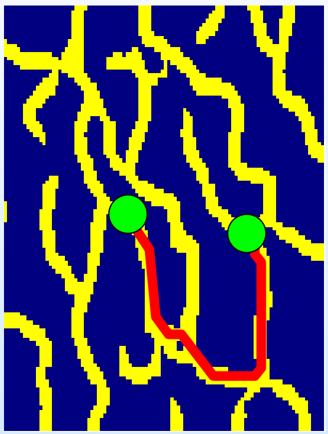


Probability map for CO_2 migration based on the models of the final cluster.

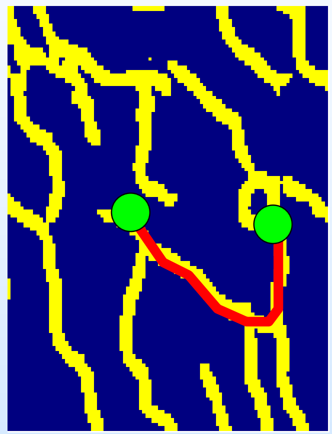
Technical Status

An Alternative Connectivity based Proxy

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



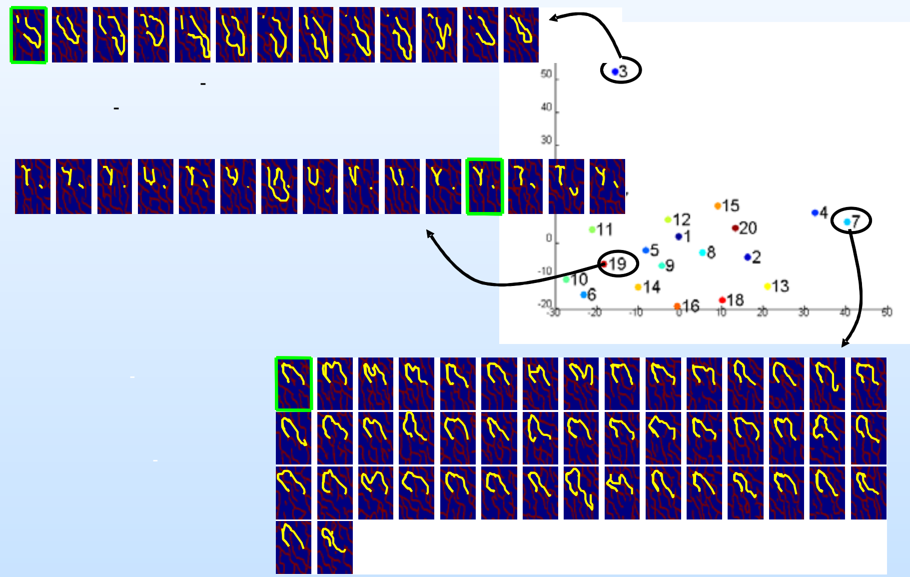
Path A1 of model #1



Path A2 of model #2

- permeable facies
- impermeable facies
- shortest path
- Inj / Prod

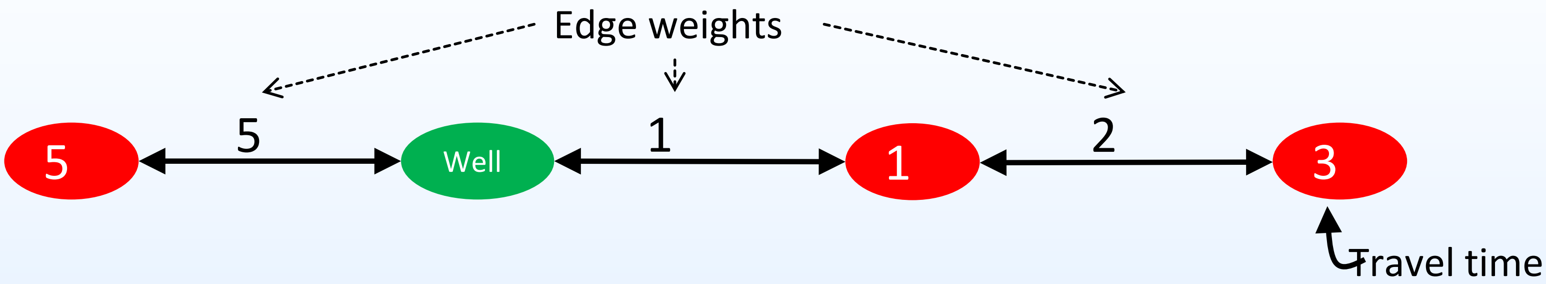
Compute discrete Frechet Distance
(points of path A1, points of path A2)



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

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

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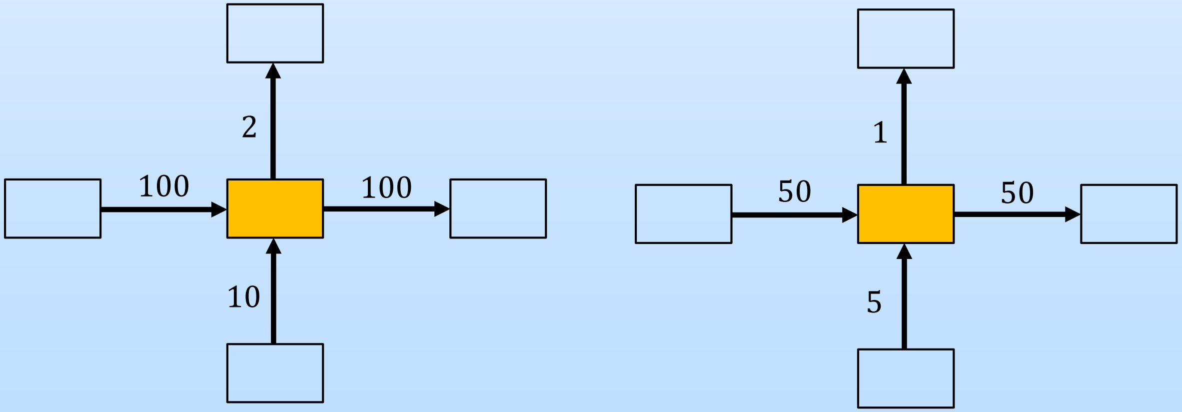
Modified Connectivity Analysis

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

$$EdgeWeight = \frac{\sqrt{V_{p_i} \cdot V_{p_j}}}{T_{ij} \cdot \Delta\Phi \cdot \mu_{CO_2}} \qquad \Delta\Phi = \Delta P + \Delta\rho g h$$

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

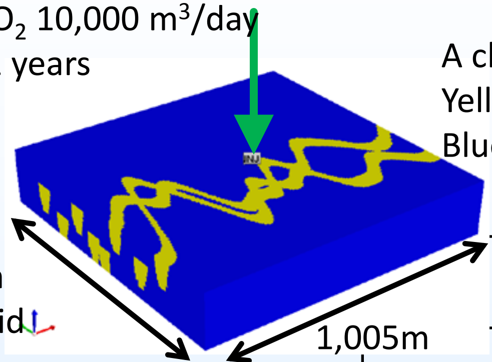


Find the minimum edge weight among the edges connected to a grid block
The edge weights are divided by the minimum value

Technical Status

Proxy Verification

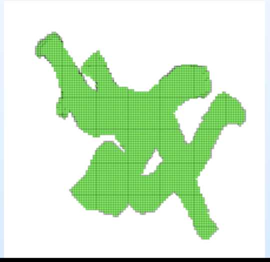
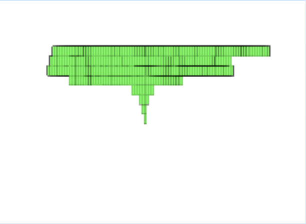
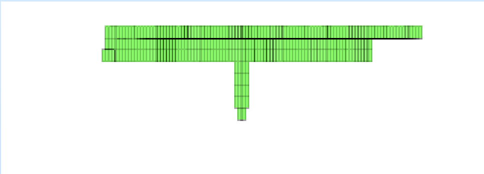
Inject CO_2 10,000 m^3/day
during 2 years



1,005m
(201 grid
blocks)

1,005m
(201 grid blocks)

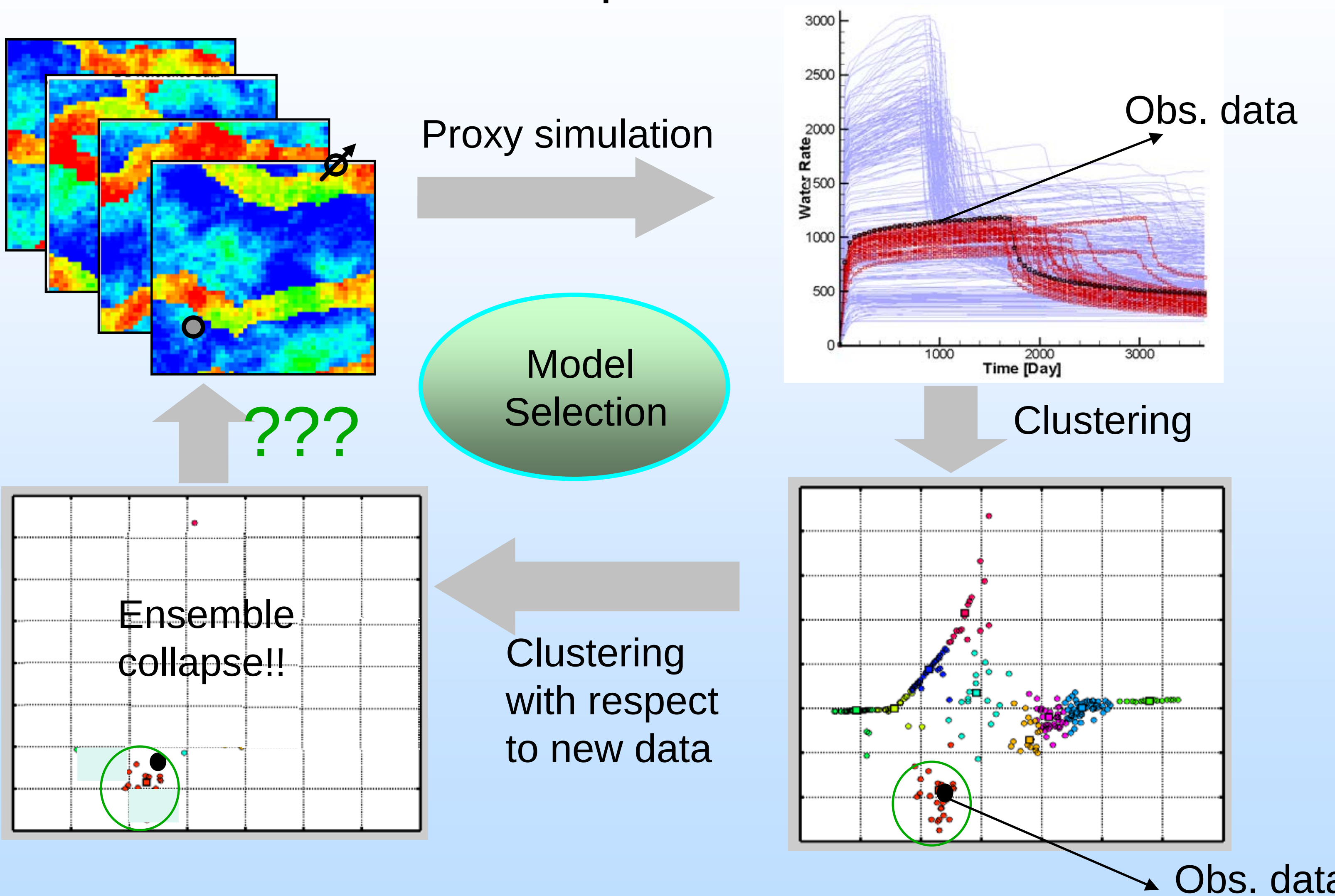
A channel reservoir
Yellow: sand, 300md, ϕ 0.2
Blue: shale, 1md , ϕ 0.1
20m (10 grid blocks)

	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

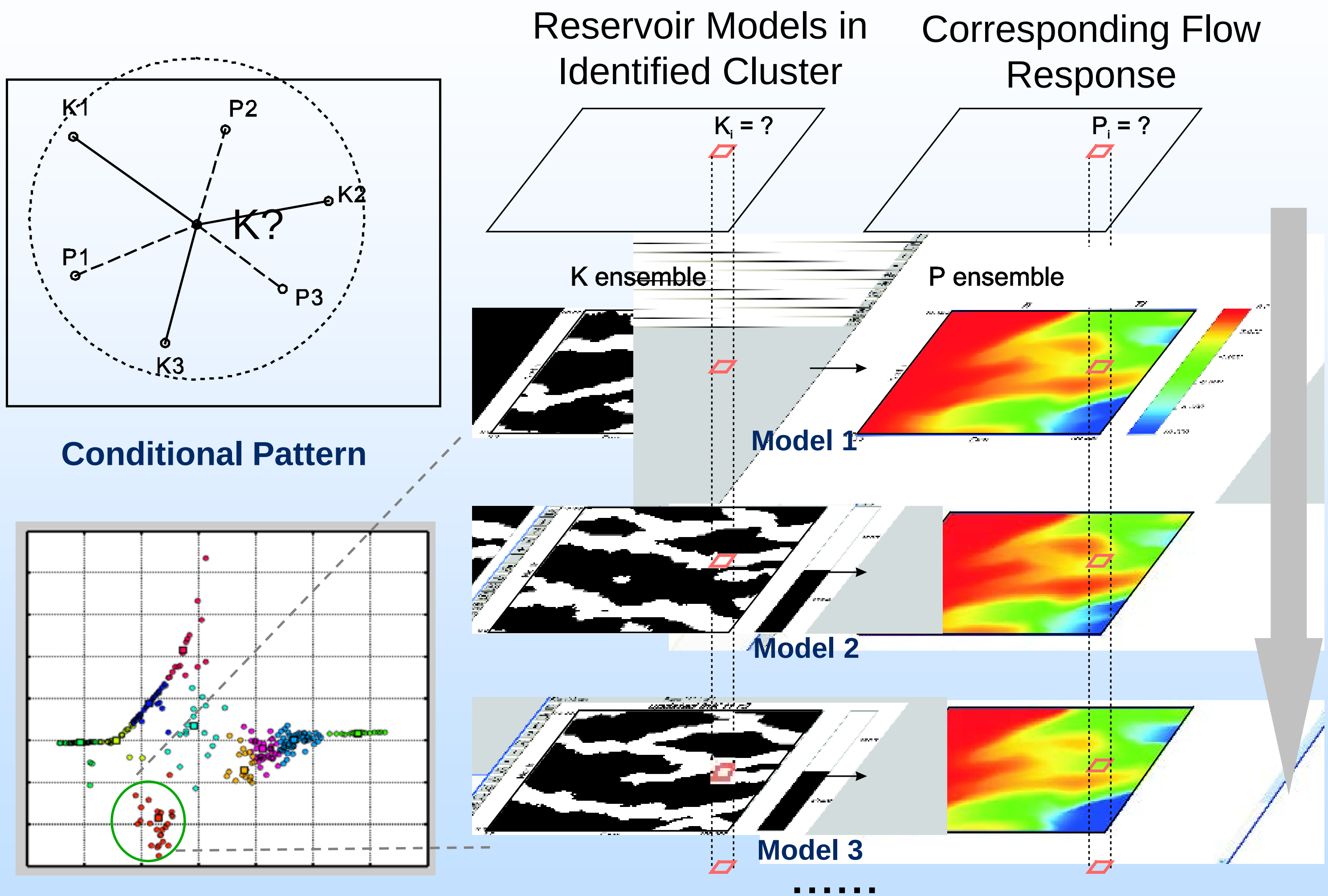
Technical Status

Model Expansion



Model expansion is necessary

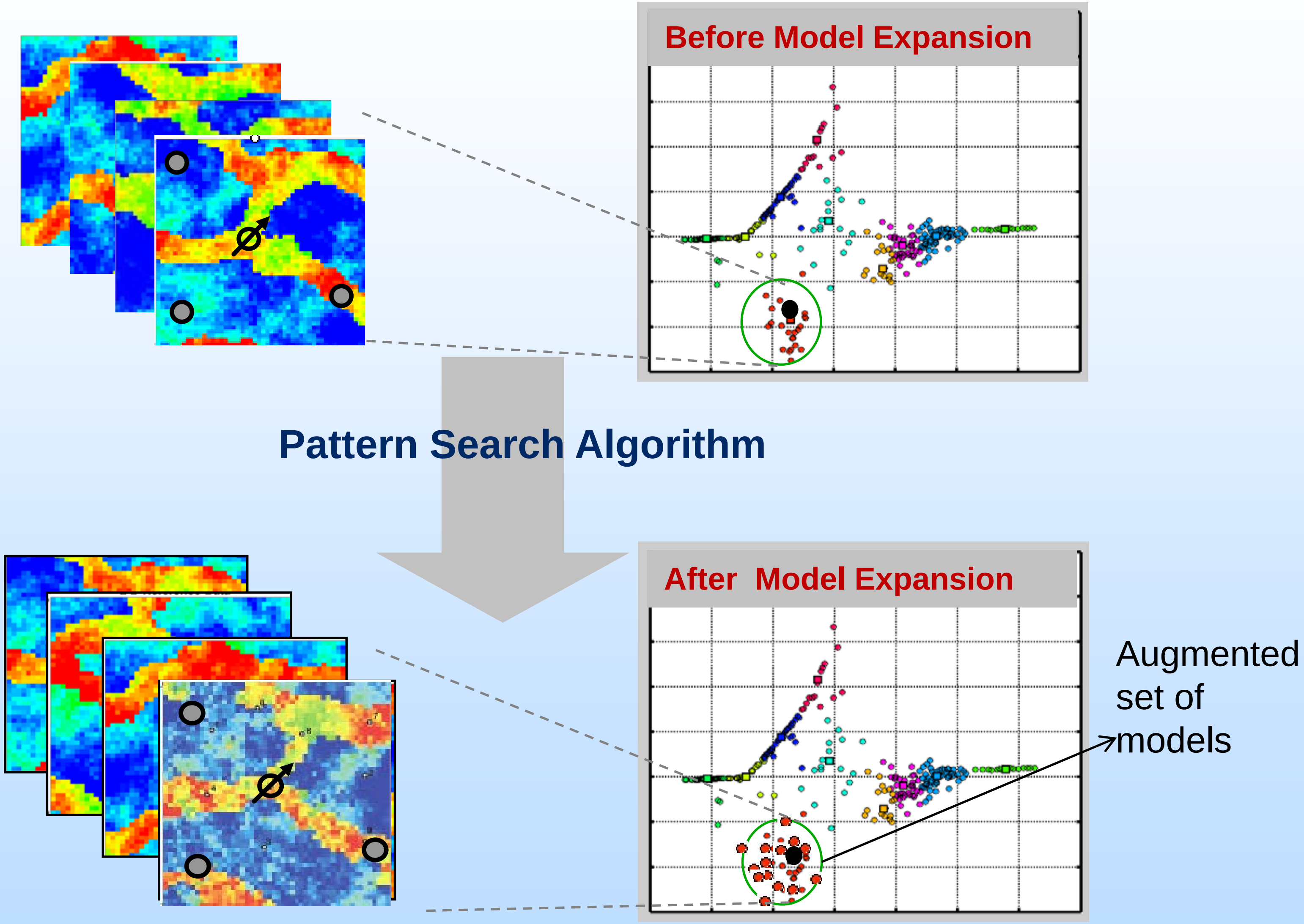
Ensemble-based pattern search



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

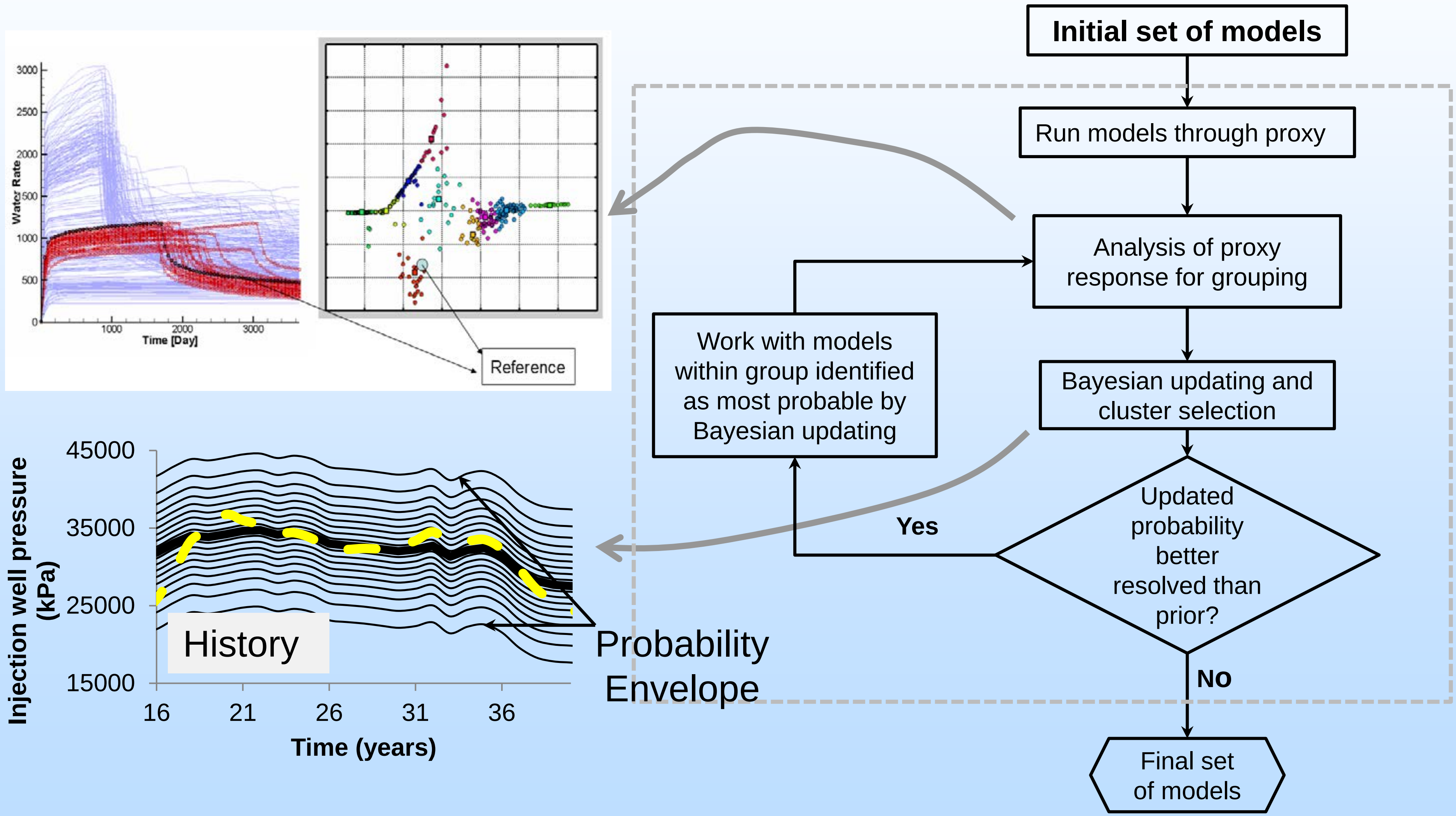
Technical Status

Ensemble-based pattern search



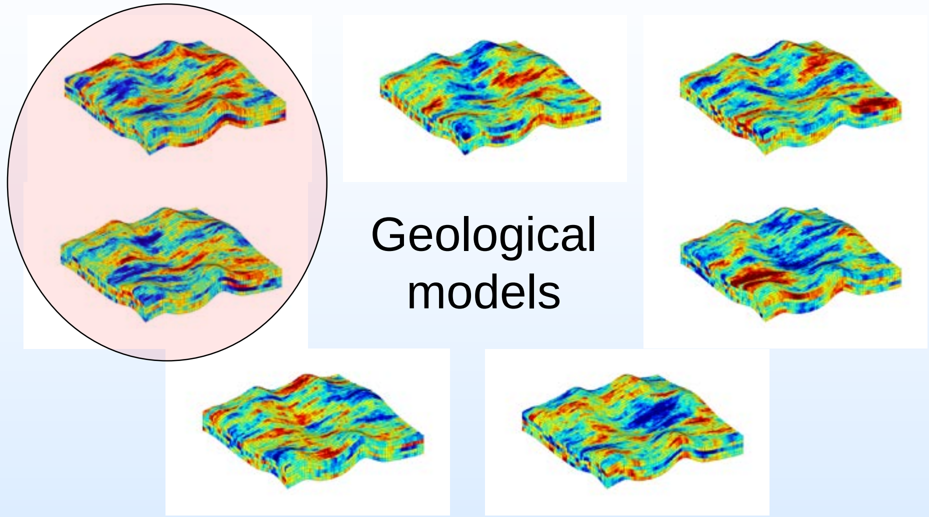
Technical Status

Integrated, modular software



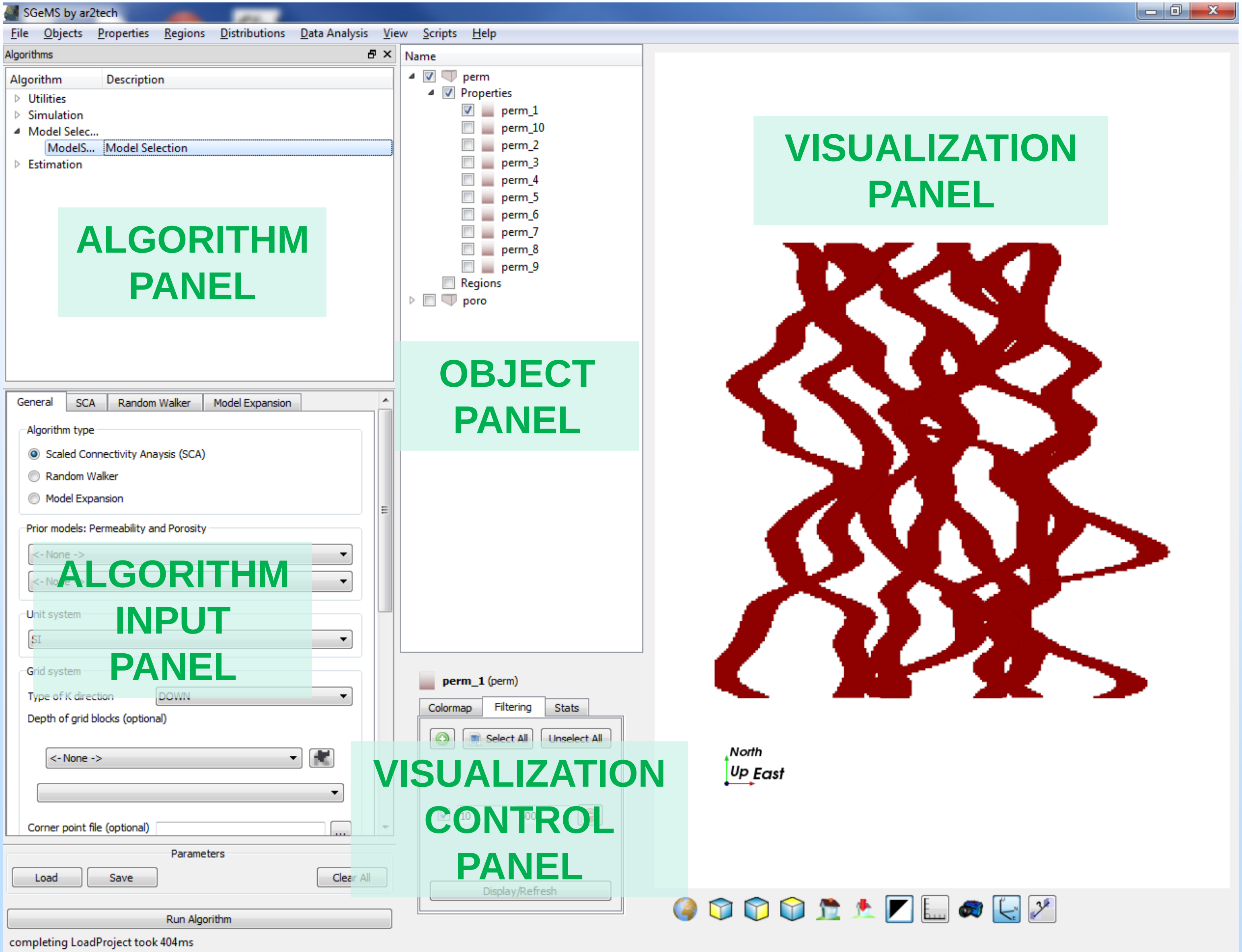
Modular Software

A set of the most probable models



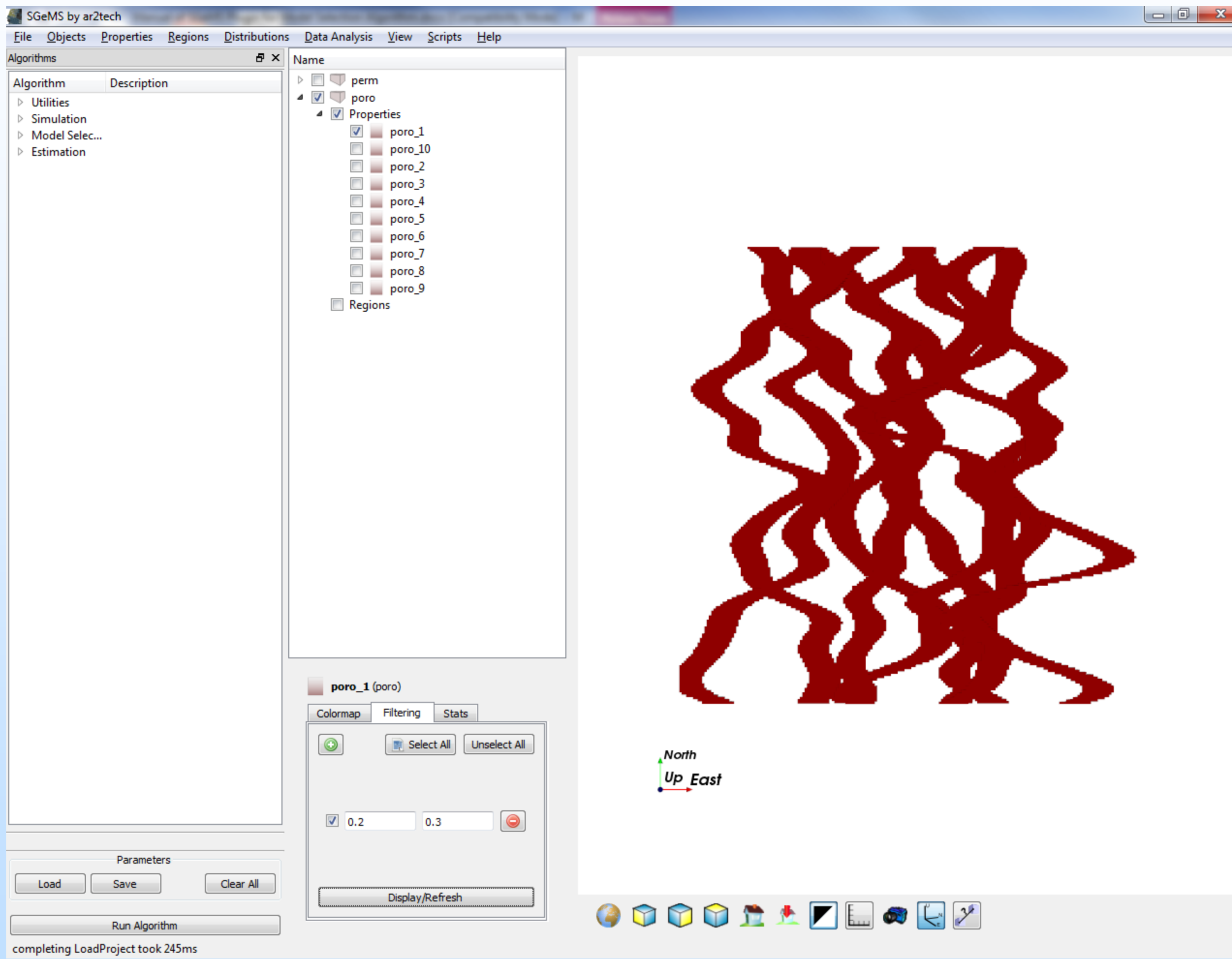
- Key objective
  - To select a set of the most probable models honoring injection data among geological models
- Software requirements
  - Separation between generating geological models and selecting in the software requires a complicated importing process
  - Allow to access geologic models directly 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



Procedure for Running the Model Selection Plugin

- Generate geological models
- Choose the model selection module in the algorithm panel
- Choose one of three model selection algorithms
- Put common input data
- Put input data of the selected algorithm
- Run



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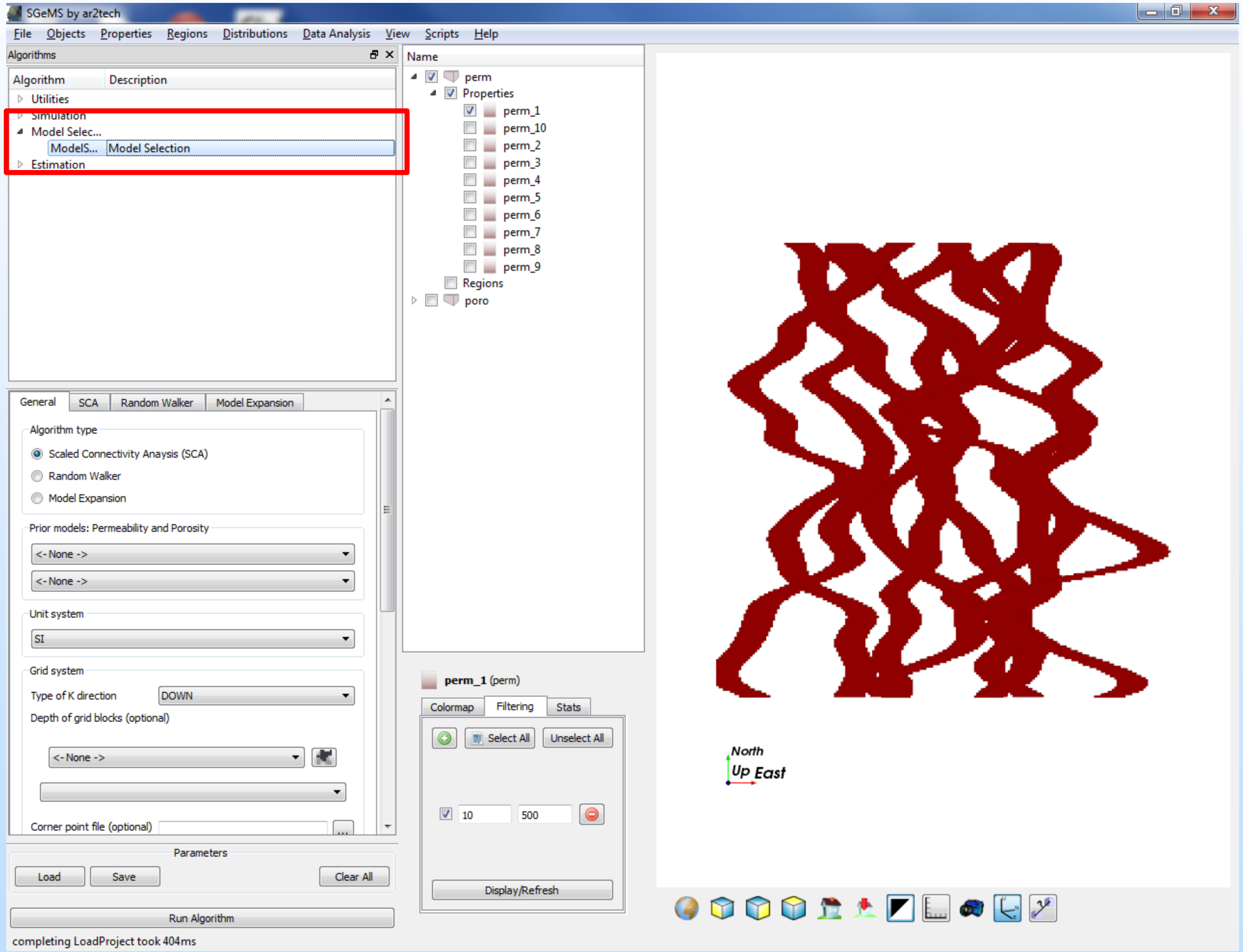

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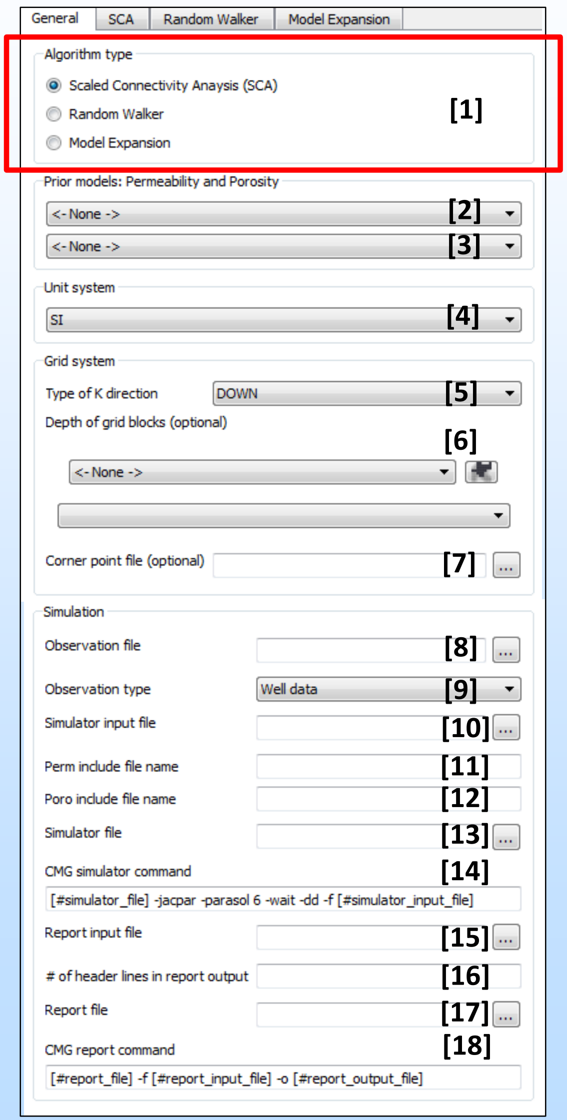
Algorithm input panel



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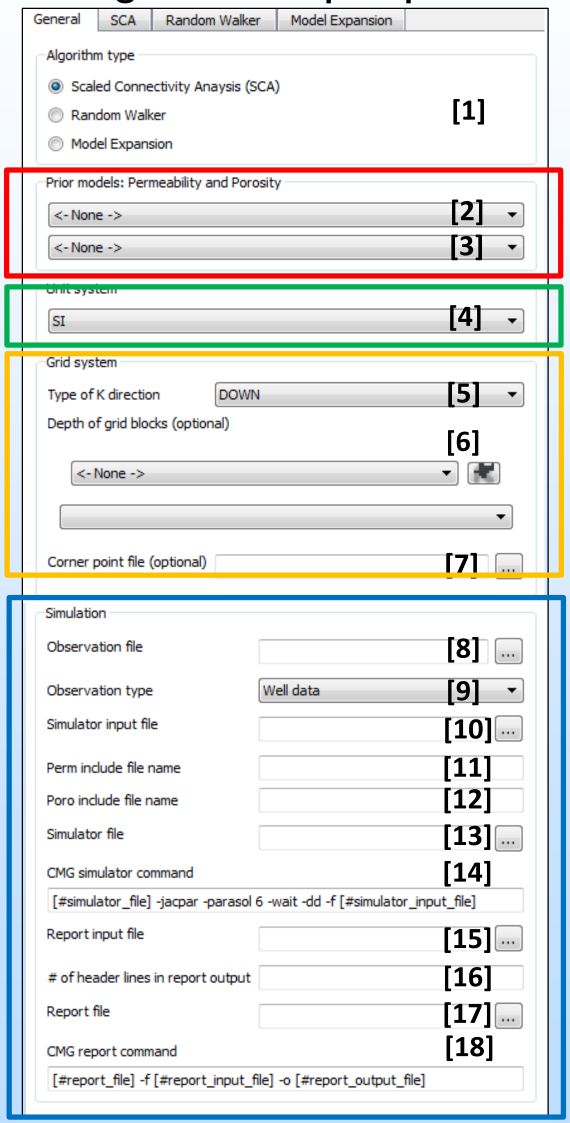
Algorithm input panel



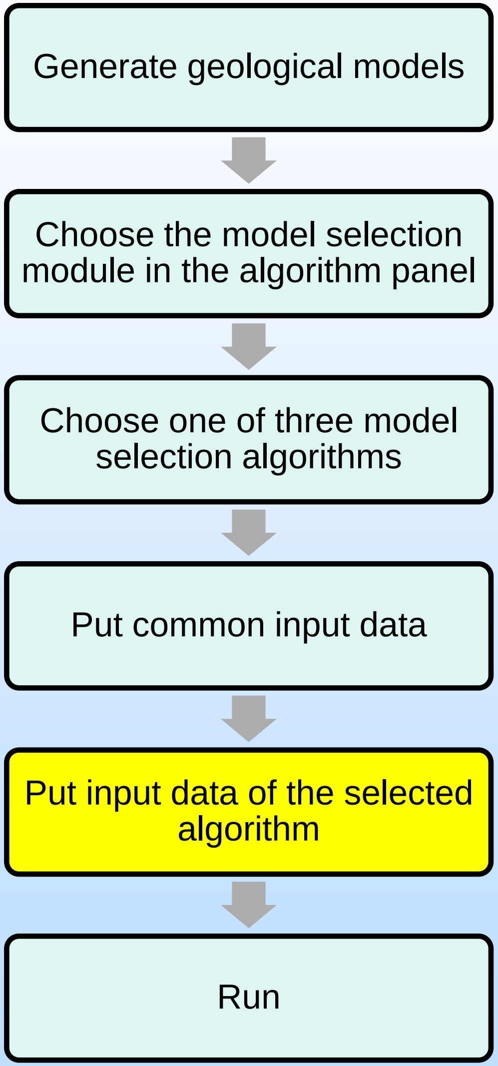
Choose prior models for permeability and porosity

Choose a unit system

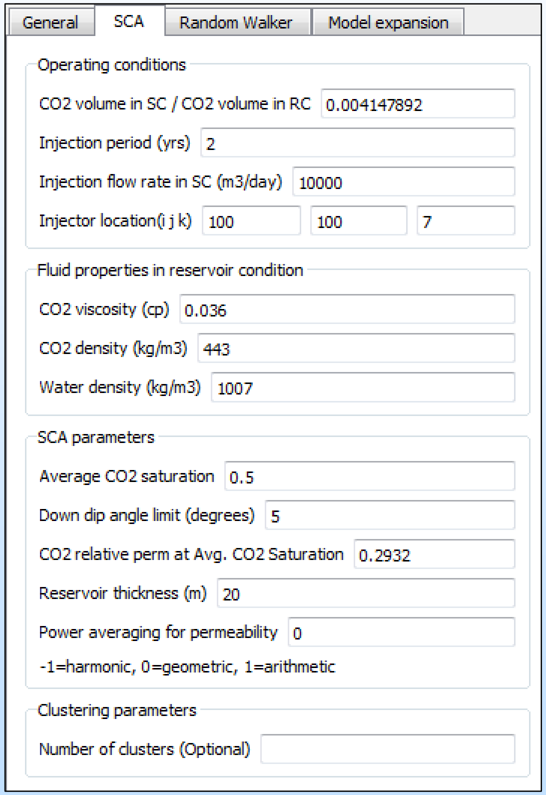
Choose a grid system (ex: K direction)

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

Procedure of Running the Model Selection Plugin



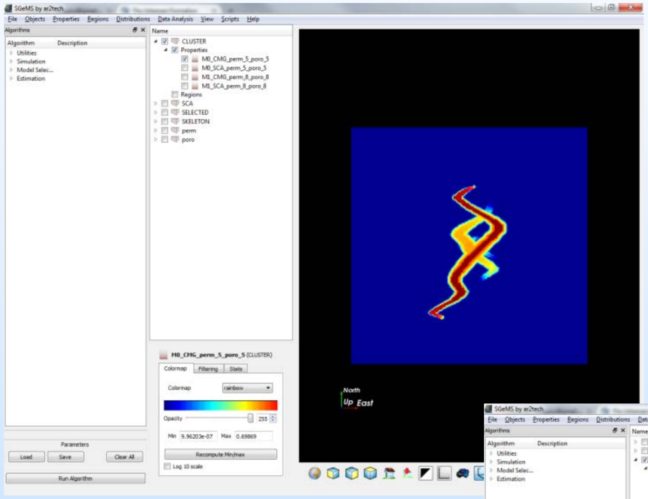
Input data of SCA



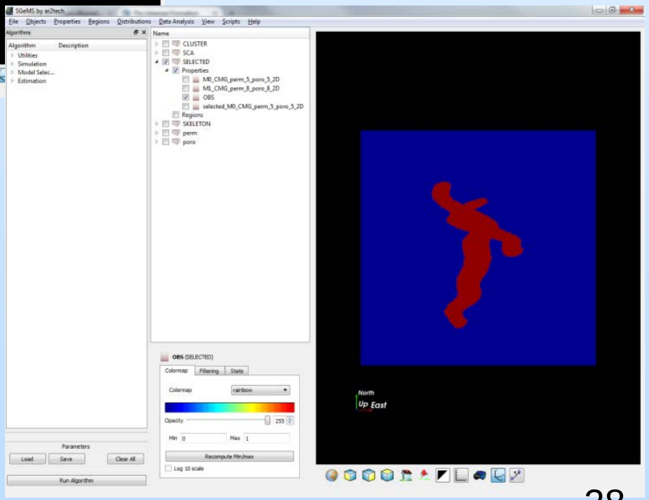
Procedure of Running the Model Selection Plugin

1. Generate geological models
2. Choose the model selection module in the algorithm panel
3. Choose one of three model selection algorithms
4. Put common input data
5. Put input data of the selected algorithm
6. Run

Simulation result of
the representative model
in the selected group



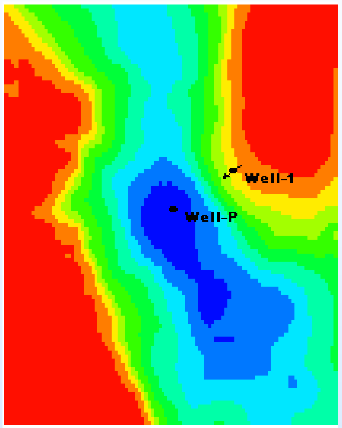
Proxy result of
the representative model
in the selected group



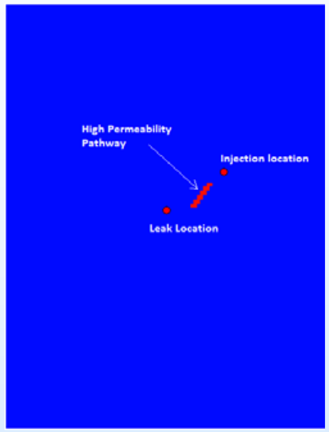
Technical Status

Effect of Unknown Leak on Model selection

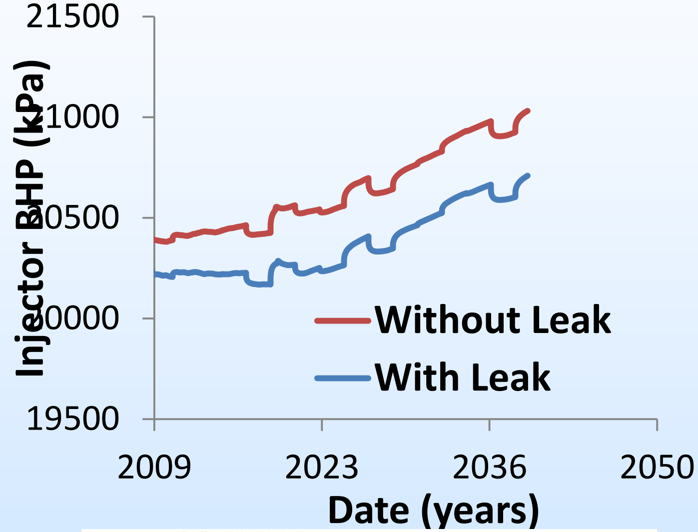
- Reservoir model for the Krechba reservoir (In Salah)

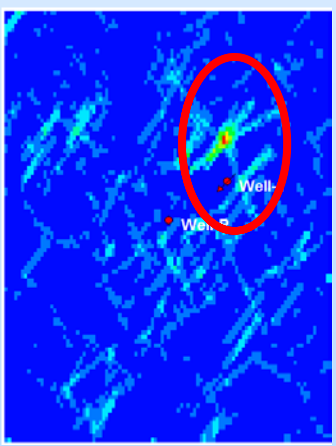


Krechba Reservoir Model

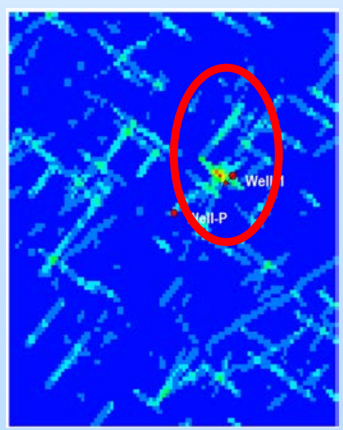


Location of injector, streak and leak

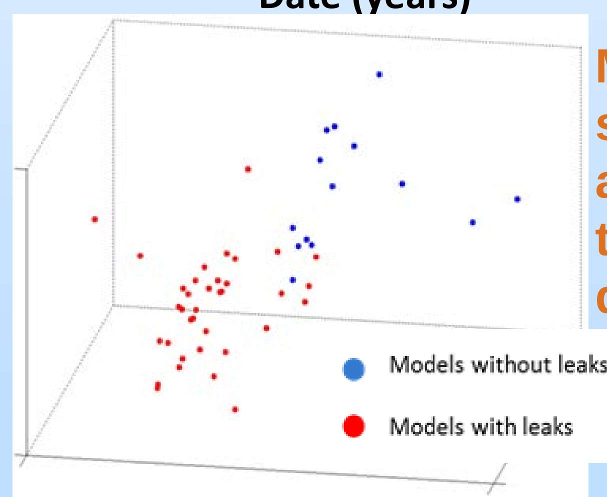




Average model when there is no leak



Average model with leak



Model selected with and without the leak are different

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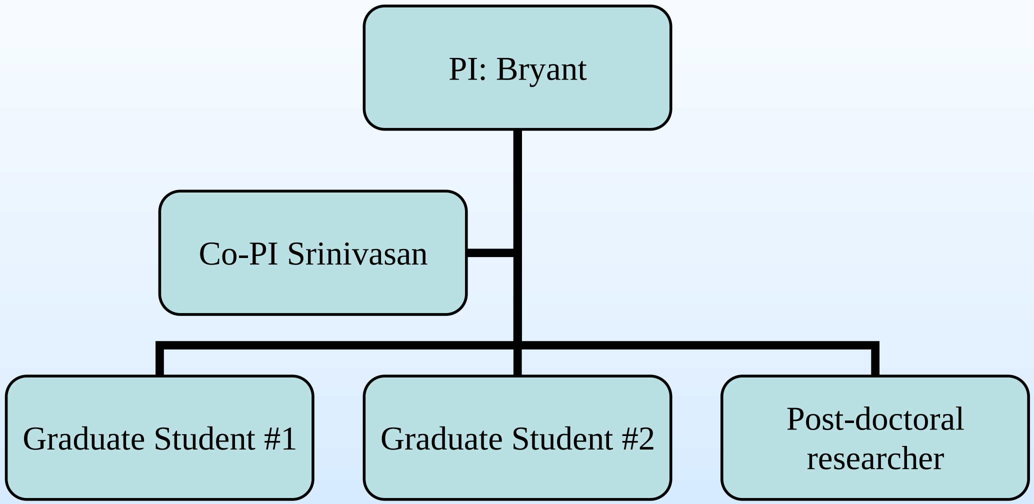
Accomplishments to Date

- 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:

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