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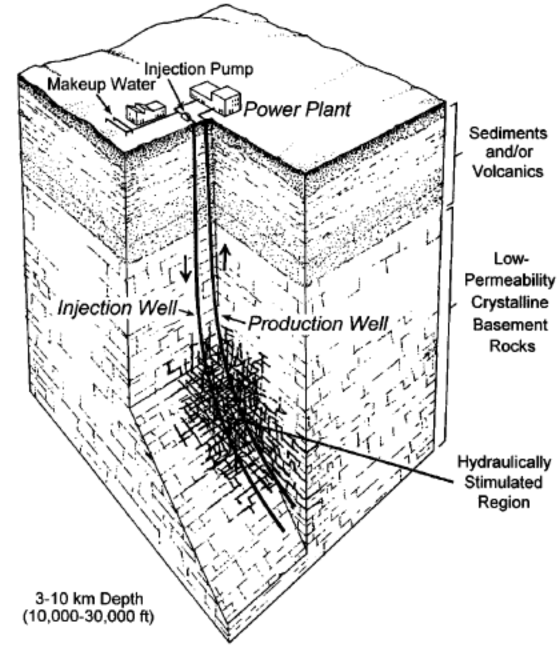

A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation

Project Officer: William Vandermeer

Total Project Funding: $528,706

May 12, 2015

Jefferson Tester

With contributions from Don Fox, Adam Hawkins and Matthew Becker

Integrated EGS R&D

Relevance/Impact of Research

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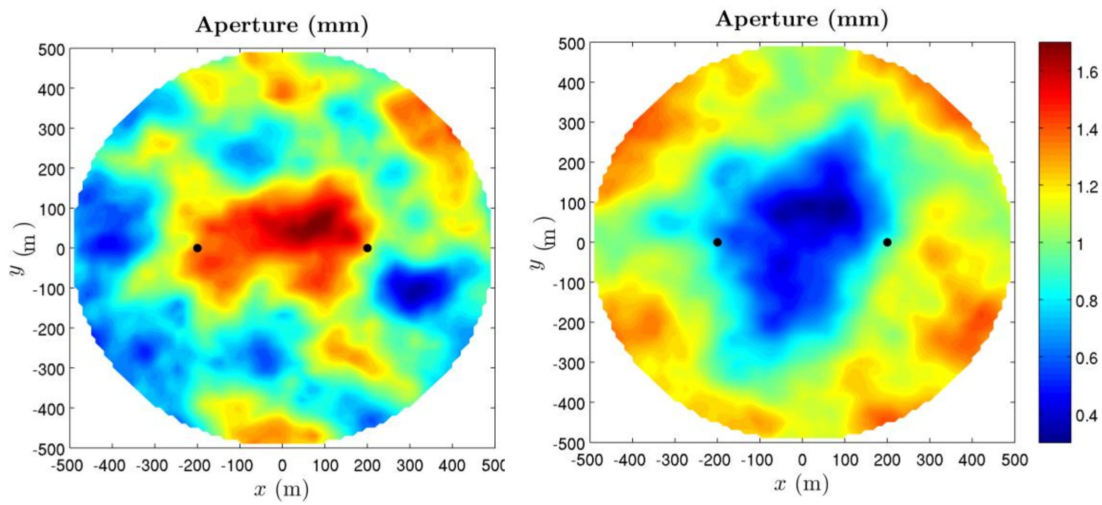
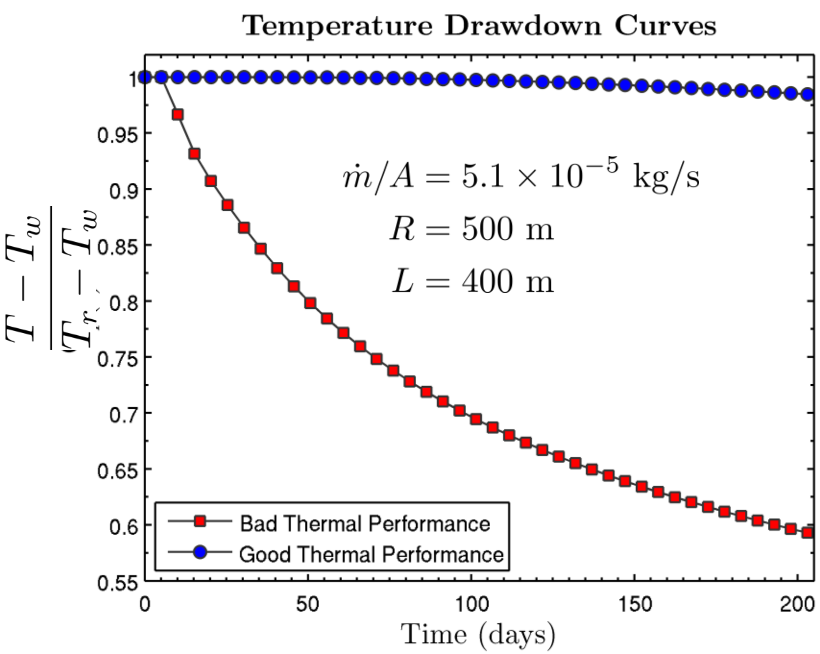
- Project Purpose
  - Use a “mesoscale” field site and numerical tools to develop procedures for reactive tracer selection and interpretation of thermal-hydraulic reservoir behavior.
- Project Objectives:
  - Develop an inversion algorithm to infer fracture geometry and thermal profile based on reactive tracers.
  - Develop new protocol for selecting a suite of tracers
  - Validate the inversion technique and selection protocol at both in a field laboratory and commercial geothermal site





Scientific/Technical Approach

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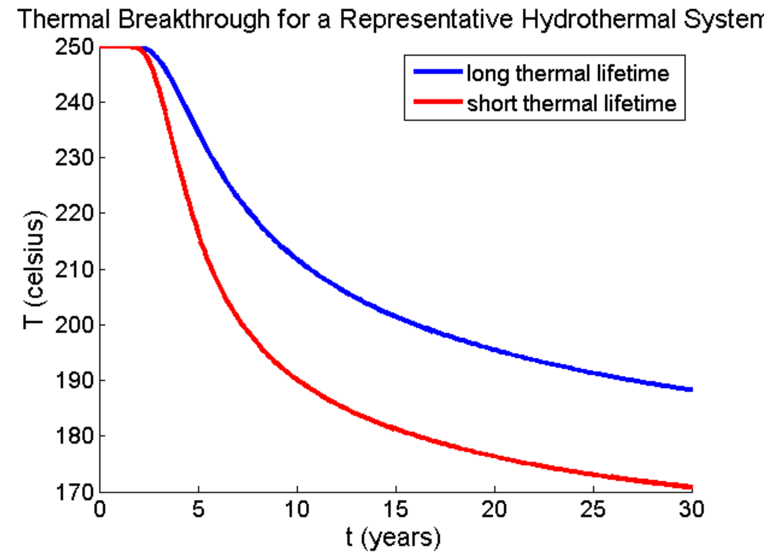
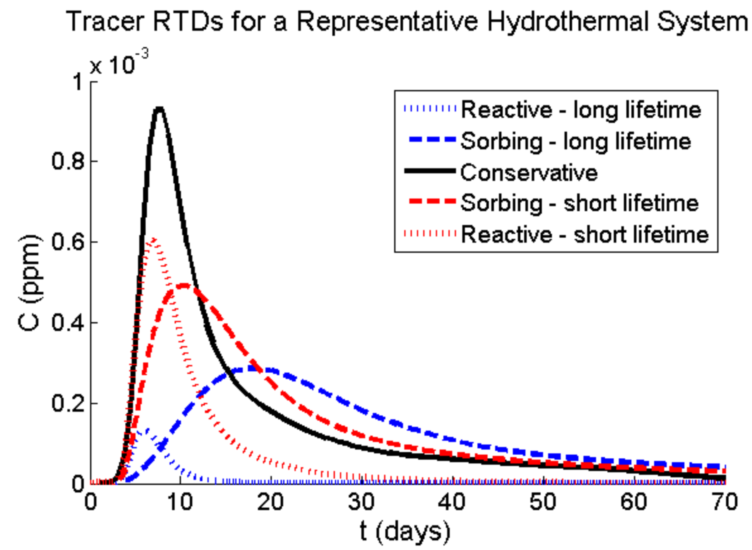
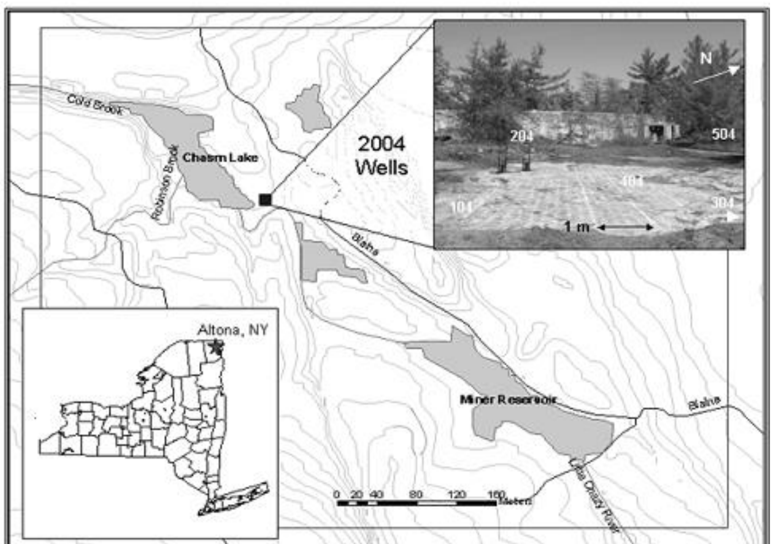
- Reactive/sorbing tracers
  - Conservative/inert tracers provide flow residence time distributions (RTD) but they cannot quantify fracture surface area available for heat exchange nor the degree of reservoir thermal depletion
  - Sorbing tracers interact with the fractured rock surface and provide a measure of surface area by comparing their RTD with that of a conservative tracer
  - Reservoir thermal performance is estimated by measuring the recovery of reactive tracer from a series of RTD measurements conducted over the lifetime of a reservoir
- Figure Descriptions
  - Upper: representative thermal performance for two different reservoirs which both have the same fracture volume, but the surface area to volume ratio differs
  - Lower: qualitative depiction of tracer RTDs. The reactive and sorbing tracer curves for the two reservoirs differ, but the conservative RTD is identical for both reservoirs

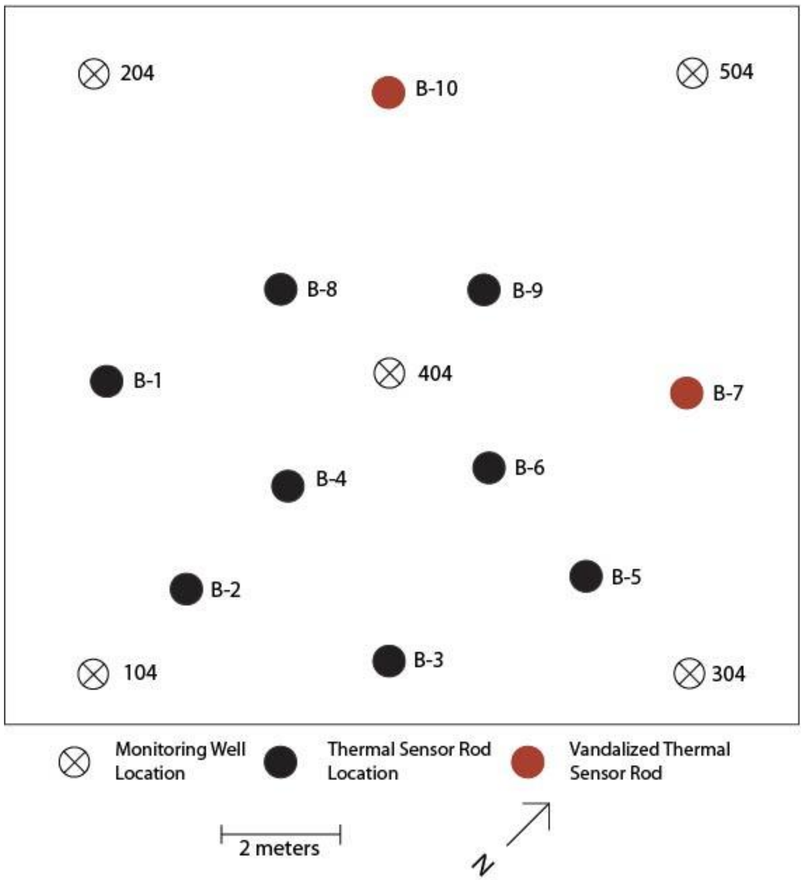




Altona Mesoscale Field Site

- Shallow sandstone with a sub-horizontal bedding plane fracture 8 meters below ground surface
- Fracture-dominated flow (porosity ~ 2%)
- 10 x 10 meter five-spot well pattern with fiber optic distributed temperature sensing (FO-DTS) installed throughout the well field

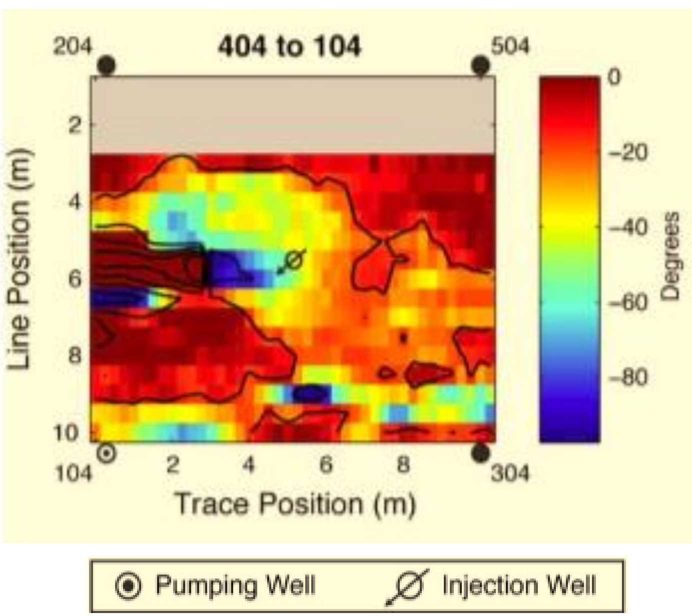




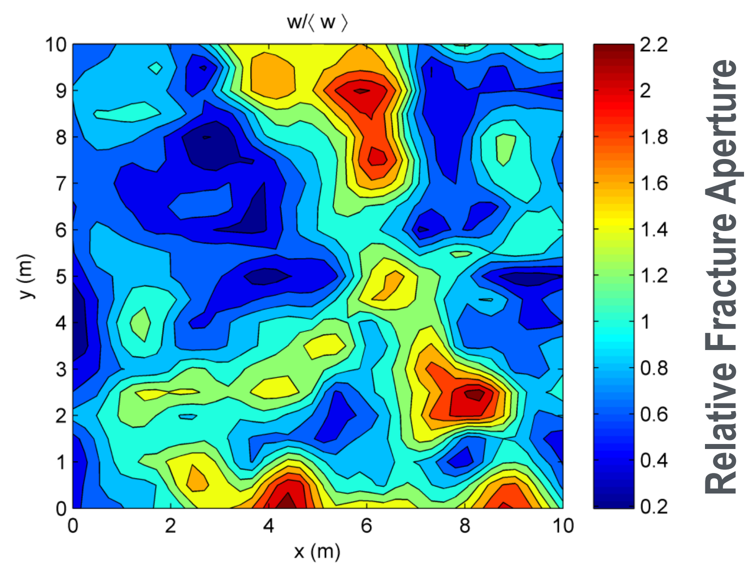
Altona Field Site results

- Fracture systems has been extensively characterized over the last 10 years, including:
  - Ground penetrating radar surveys (GPR), caliper logs, gamma logs, formation electrical conductivity logs, slug tests, pump tests, tracer testing, and heat exchange experiments

GPR Imaging of saline tracer path



Inferred Fracture Aperture Based on GPR Reflection Amplitude



Transitioning from field measurements to tractable model of aperture distribution

- Principal Component Analysis (PCA)
  - Model reduction via determining dominate modes
  - Describing spatially varying aperture field by modeling the reservoir with 4-24 dominant modes
- Genetic Algorithm (GA)
  - Heuristic global optimization/minimization
  - Mimics natural selection using individuals (models) with a phenotype (value of model parameters) and fitness score (value of objective function) and mutations
  - Easily parallelized
  - Search for basis functions' parameters of aperture field and obtain tracer curves
  - Minimize the least squares error between the measured and predicted tracer residence time distribution (RTD)

Mode Coefficient **PCA Modes**

$$w\left(\mathbf{r}\right) = \alpha_1\{\Phi_1\} + \alpha_2\{\Phi_2\} + \alpha_3\{\Phi_3\} + \ldots + \alpha_N\{\Phi_N\} = \Phi_{ij}\alpha_j .$$

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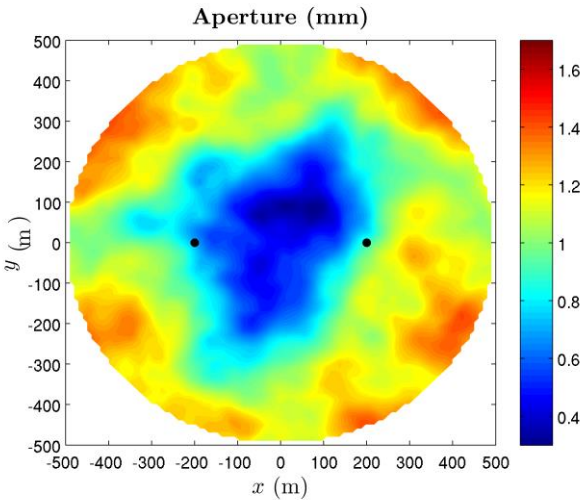
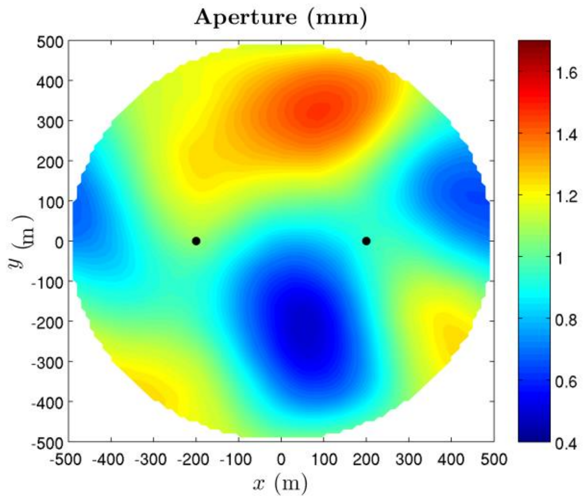
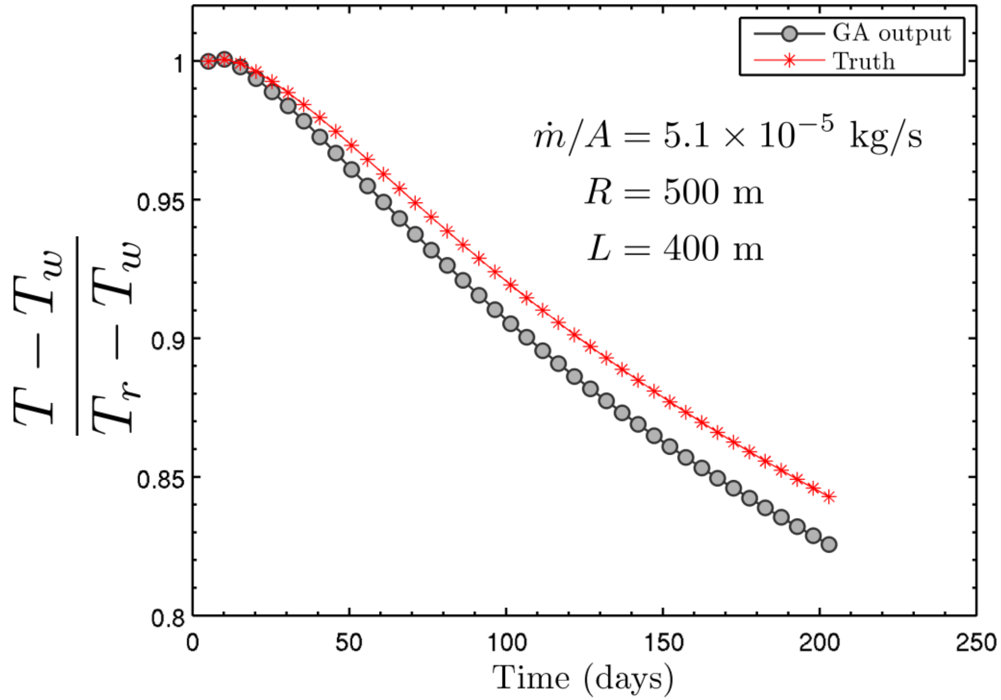
Target Aperture Field



GA Output 16 modes

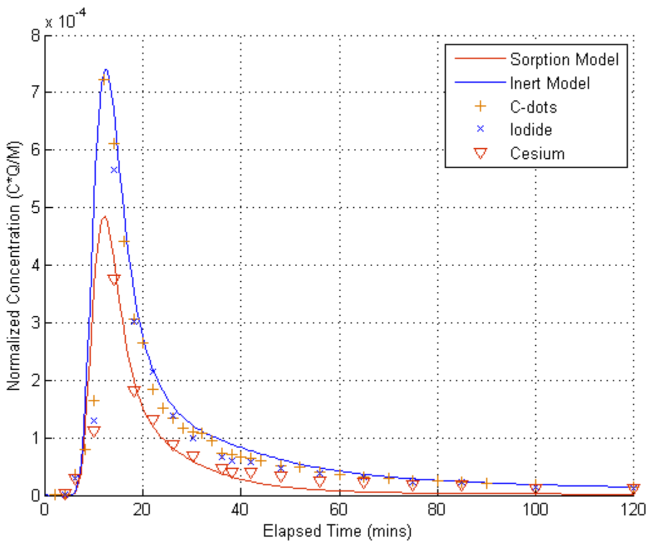




Successfully demonstrated that the GA is capable of capturing the essential features of the experimental aperture field. In addition, we have been able to produce quantitative agreement with modeled thermal drawdown for the actual flow case.

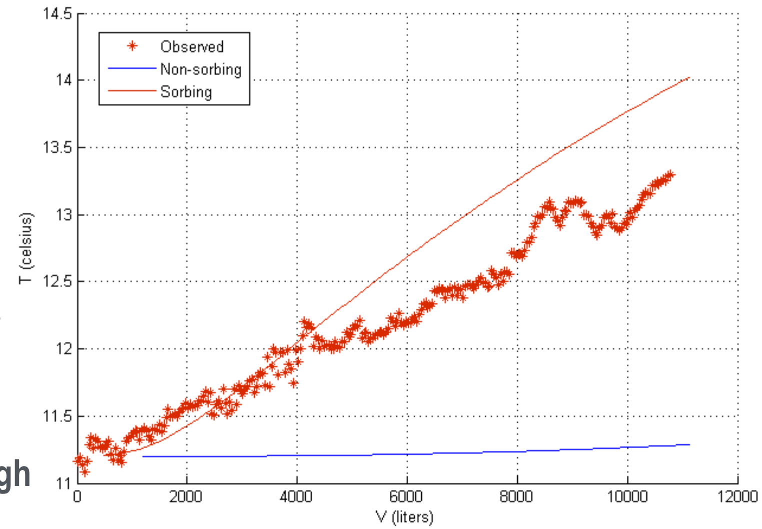
Accomplishments, Results and Progress for Altona field tests

Predicted vs. Observed Tracer RTD



Inferred parameters from each model used to predict thermal breakthrough

Predicted vs. Observed Thermal Breakthrough

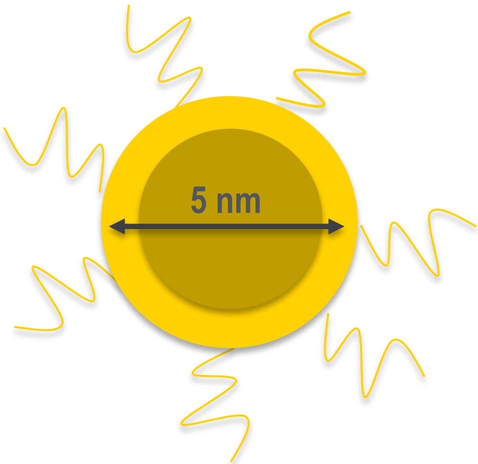


Simulated tracer curves produced via a constant aperture, dipole-flow model includes the combined influence of advection, dispersion, and rate-limited adsorption. Fits to observed data were obtained by varying the fracture aperture, dispersivity, and the retardation factor. The observed data consisted of three tracers – two conservative and one sorbing.

Thermal breakthrough was predicted, first based on the best fit fracture aperture from the conservative tracer test, labeled above as the “Non-sorbing” curve. The second prediction, labeled above as “Sorbing”, was made based on the surface area inferred from the best-fit sorbing tracer curve which is clearly a better indicator of thermal performance.

Nanoparticles & Current Milestone Summary

- Developed "Carbon Dot" (C-Dot) tracer at Cornell (Krysmann 2012)
- Carbon core decorated with highly fluorescent polymer
- Consists of citric acid and ethanolamine
- Environmentally benign and detectable at > 10 ppb
- Stable up to 200^{o}C – active research ongoing to raise stability to 300^{o}C
- Altona field experiments demonstrate C-Dots behave conservatively



Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Milestone 1.1 Successful application of inversion method in simulated environment	same	January 15, 2015
Milestone 3.1 Generate reservoir performance probability	Thermal performance predicted from simple analytical models using sorbing tracer test interpretation – to be readdressed later in project	January 30, 2015
Milestone 4.1 Selection of tracer compounds to be used at Altona	Same	March 31, 2015

Future Directions - Fieldwork

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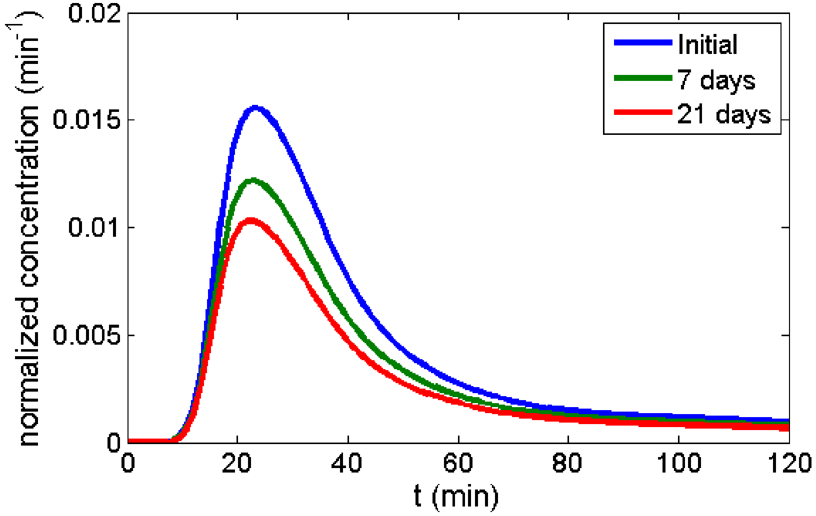
- Summer (2015) Field Work
  - Reactive tracers at Altona field site with hot water injection
  - Reactive, Sorbing, and nanoparticle tracer test at the Hubbard Brook Experimental Forest in New Hampshire with hot water injection (In collaboration with Professor Matt Becker - Cal State, Long Beach)
- Laboratory work
  - Further quantification of cesium sorption behavior onto sandstone surfaces



Milestone or Go/No-Go	Status & Expected Completion Date
M 2.1 Inversion of Altona tracer data to produce family of reservoir aperture distributions	planning stage; 6/30/15
M 3.1 Generate reservoir performance probability	in progress; 6/30/15
M 5.2.1 Thermal breakthrough recorded at production well in Altona field experiments	planning stage; 09/28/2015
M 5.3.1 Successful completion of reactive tracer tests at Altona	planning stage; 09/28/2015

Future Directions - Modeling

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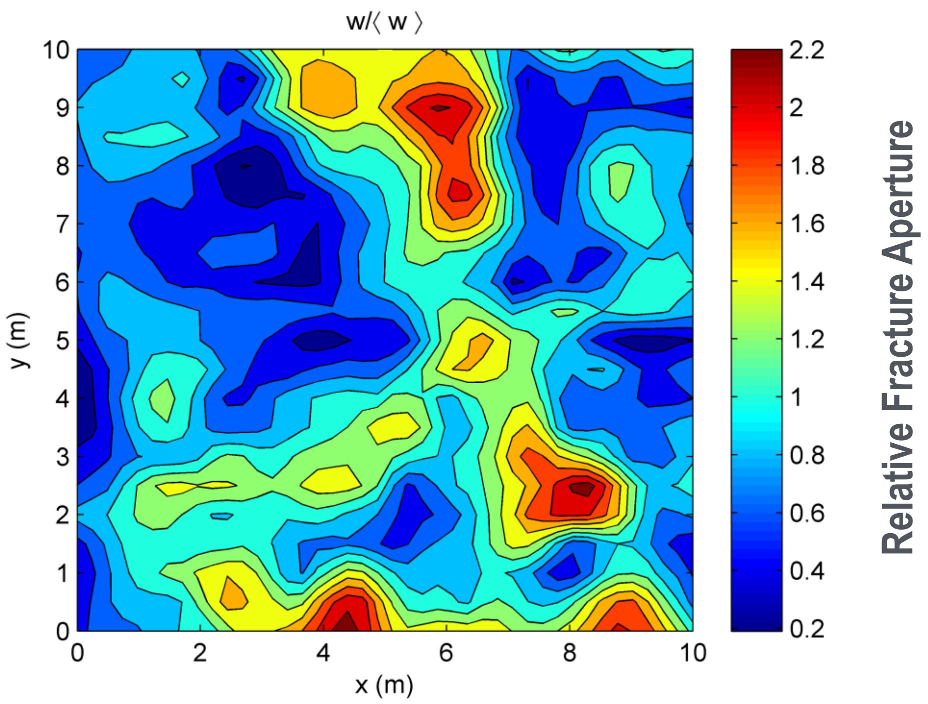
Apply modeling methods to Altona field data and representative EGS fractured reservoirs

- Refine Current Modeling on Simulated Fractures
  - Explore range of commercial sized reservoir systems
  - What is the ideal number of PCA modes to use
  - What is the best objective function to use (step, pulse, median time, etc.)
- Altona Field Site
  - Validating PCA modeling approach using Altona field GPR data: aperture distribution, flow, and thermal response
  - An inverse search using the GA will approximate the aperture field using real tracer results

Inferred Fracture Aperture Based on GPR Reflection Amplitude



Summary

- Fundamental understanding of thermal/hydraulic behavior in the subsurface is crucial in evaluating and operating a commercial geothermal reservoir.
- Our project provides access to a unique field site that is well characterized and enables thermal/hydraulic measurements using tracers that can be compared with model predictions.
- We are making progress on two fronts:
  - Numerical: Developing an inversion algorithm to determine the spatially varying aperture field
  - Experimental: Have already run experiments on sorbing tracers and will run thermal degrading tracer tests soon

References

- Krysmann, M. J., Kelarakis, A., Dallas, P., & Giannelis, E. P. (2012). Formation Mechanism of Carbogenic Nanoparticles with Dual Photoluminescence Emission. Journal of the American Chemical Society, 134(2), 747-750. doi: 10.1021/ja204661r