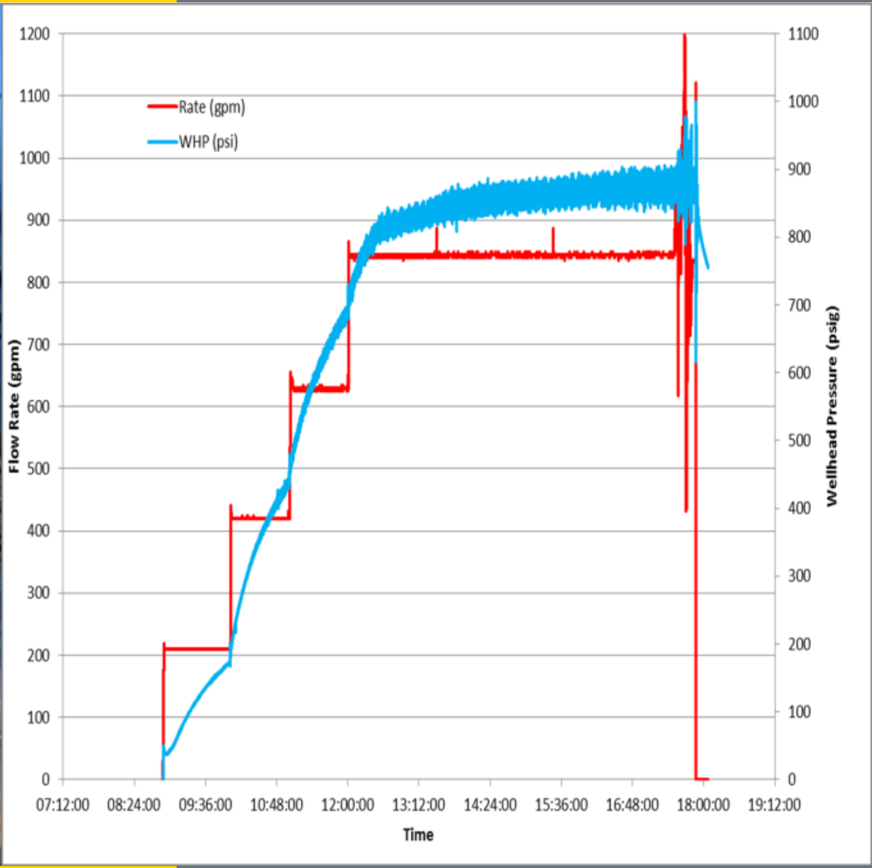


EGS Reservoir Simulations & Long-term Performance Modeling

Project Officer: Lauren Boyd

Total Project Funding,: $208,041

May 31, 2015

Principal Investigator: Rob Podogorney

Presenter: Mitchell Plummer

Idaho National Laboratory

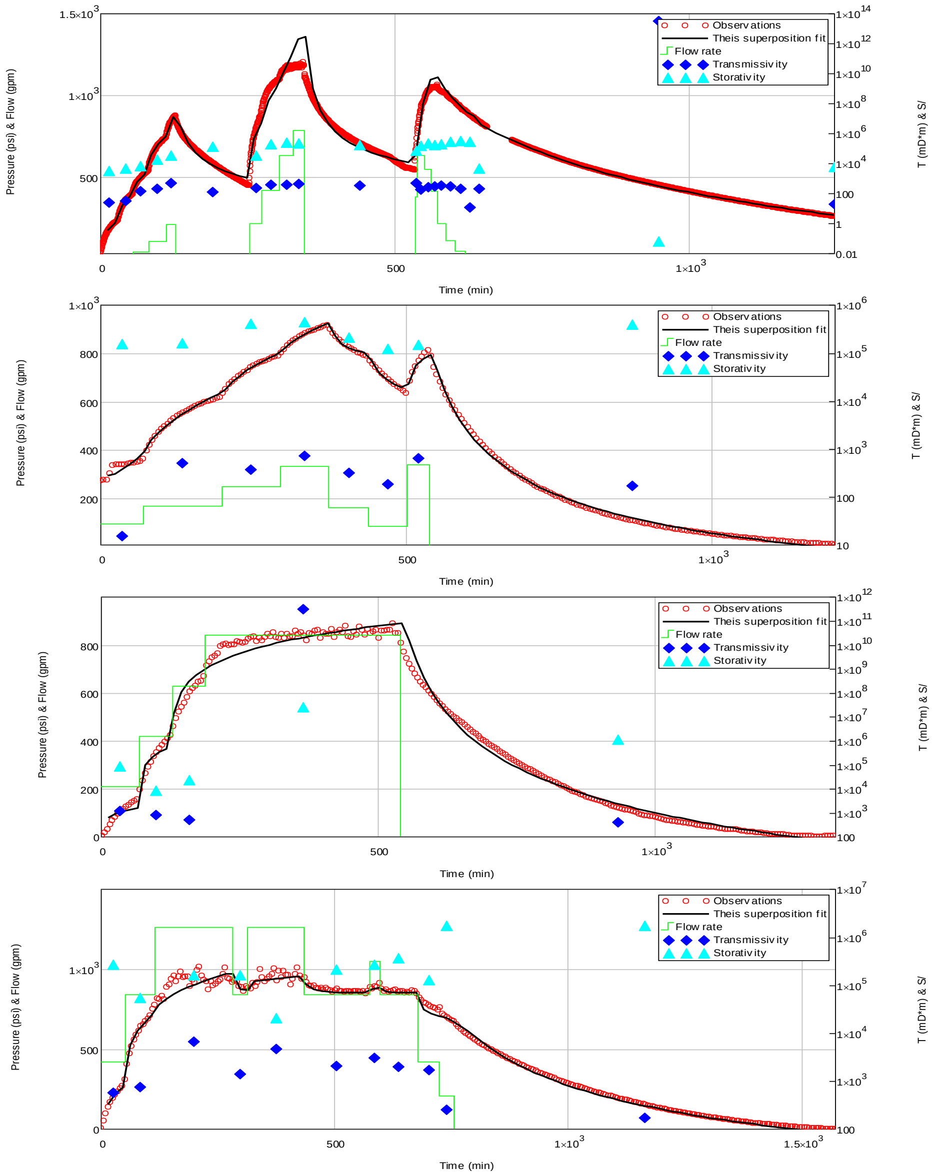
EGS

Relevance/Impact of Research

- Project objectives
  - Interpret RRG-9 pressure/flow response to improve understanding of reservoir response to stimulation
  - Use numerical simulation to test hypotheses about reservoir response to high-pressure / low-temperature well stimulation
- Challenge: Reservoir creation via well stimulation is the key to EGS development, but limited data exist regarding geothermal reservoir response to thermal and high-pressure injections. Analysis of those data is required to understand impact.
- Impact on EGS development: Demonstrated success of stimulation tests will provide risk reduction necessary to motivate industry to attempt EGS.
- Innovation: Many existing codes use sequential coupling to solve THMC problems. Code development in INL's MOOSE framework attempts to use fully implicit, fully coupled approach.
- Impact to GTO goals: Reducing risks of EGS development is the first step toward industry deployment of a targeted 100+ GW of EGS.
- Integration: Analyses support the larger "**EGS – Concept Testing and Development at Raft River**" under direction of Joe Moore

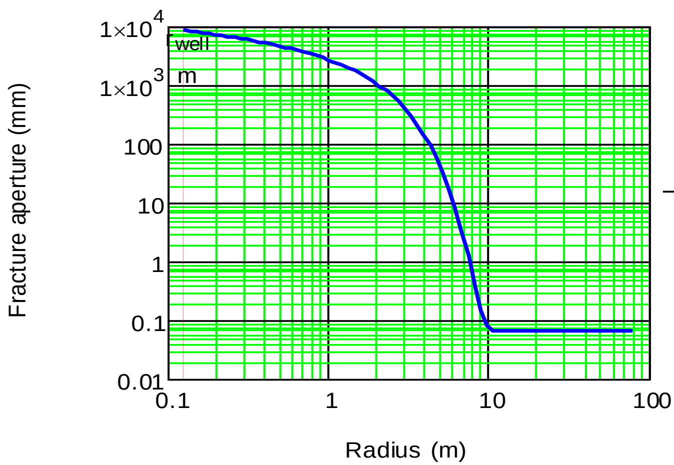
Scientific / Technical Approach

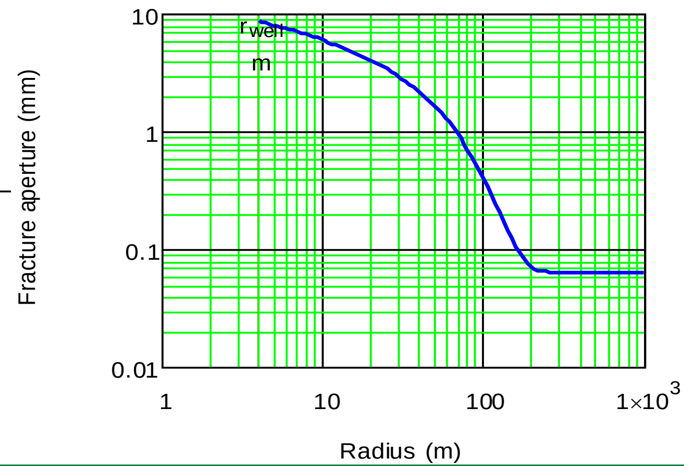
1. Apply multiple methods of analysis to provide explanations for observed response to stimulation
   - Standard well hydraulics diagnostics
   - Numerical simulation, using thermo-hydraulic-mechanics simulations
2. Modify FALCON code to extend implicitly coupled fracture mechanics, fluid flow & heat transfer capabilities
3. Develop simulations to test hypotheses about reservoir
   - What models are consistent or inconsistent with hydraulic data?
     - narrows zone permeability,
     - primary fracture extent,
     - response at other wells, …



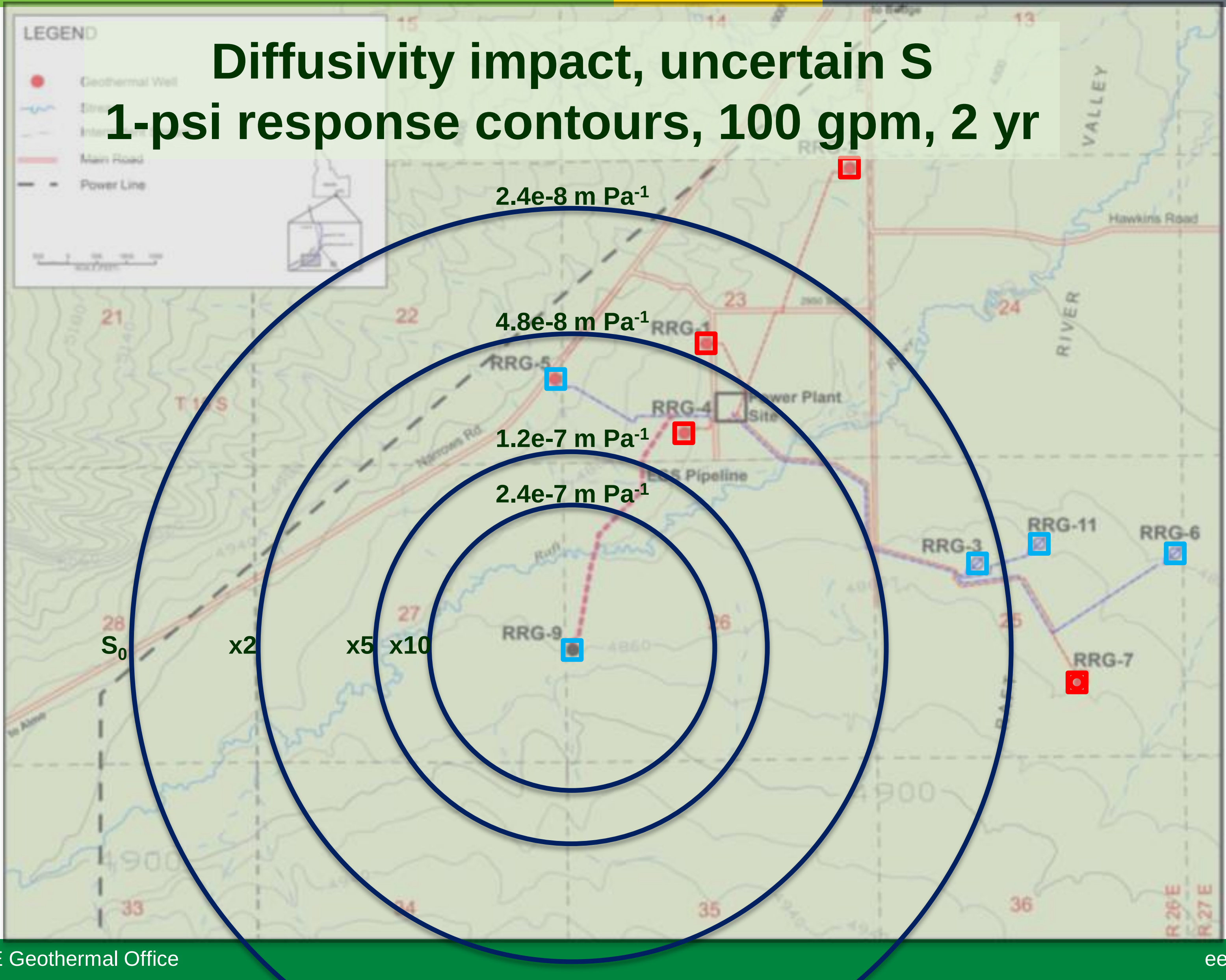
Inference from pumping test anlaysis

- Response to lowest pressure injection provides best estimate of initial permeability and compressibility.
  - Transmissivity (permeability x thickness) ~ 2e-14 m^3 (9.7e-7 m^2/s)
- Slow pressure rise suggests unrealistic compressibility,
  - Suggests presence of large fracture that effectively extends wellbore to several meters radius.
  - Consistent with borehole televiewer data and temperature profiles
  - Note that dilation-induced changes in permeability would act to steepen pressure response, □ apparent lower storativity



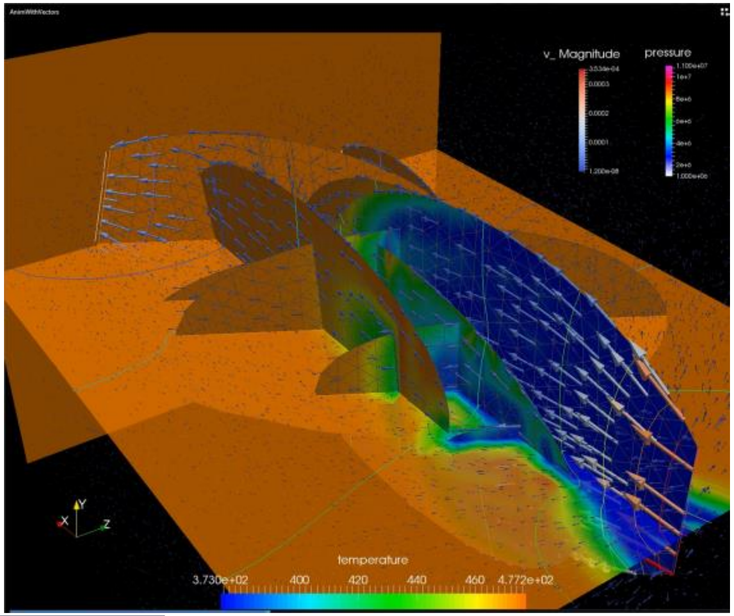


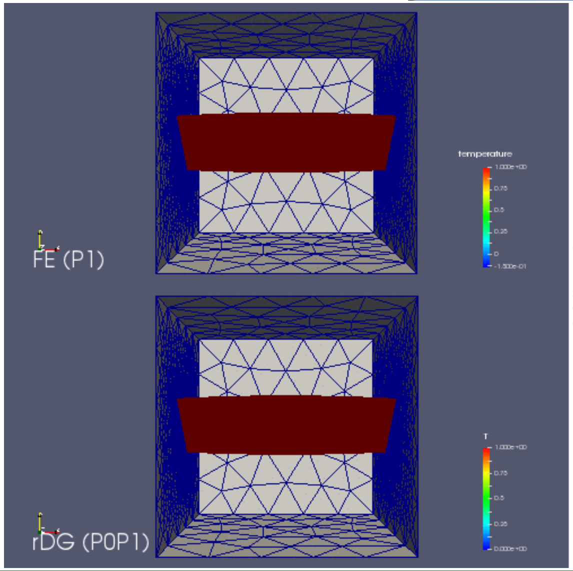
Diffusivity impact, uncertain S

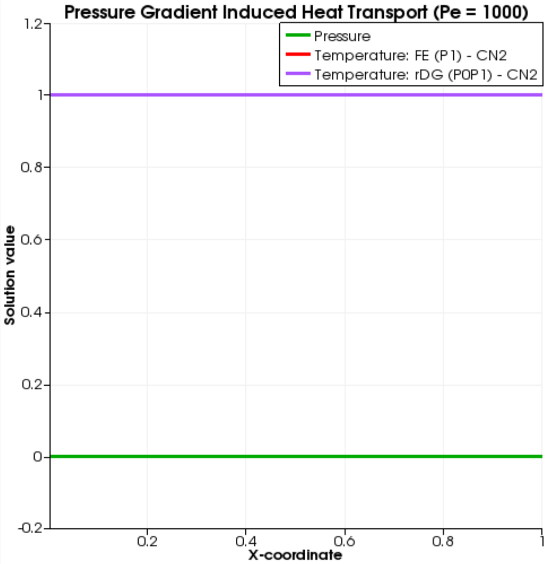


FALCON improvements

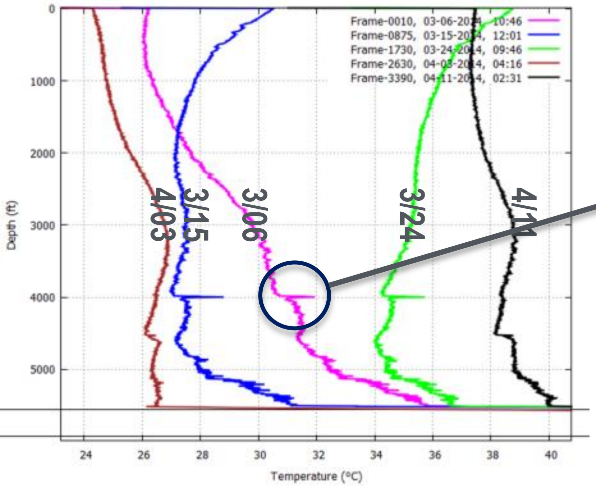
- Developed solution method for use of lower-dimension domains in higher dimension models (eg. 2D fracture in 3D domain)
- Added reconstructed discontinuous Galerkin method for high Peclet-number problems
- Replaced mechanics with tensor mechanics approach
- Developed well model
- Developing cohesive zone model for fracturing approach in finite elements

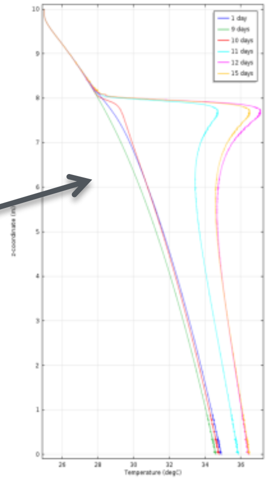




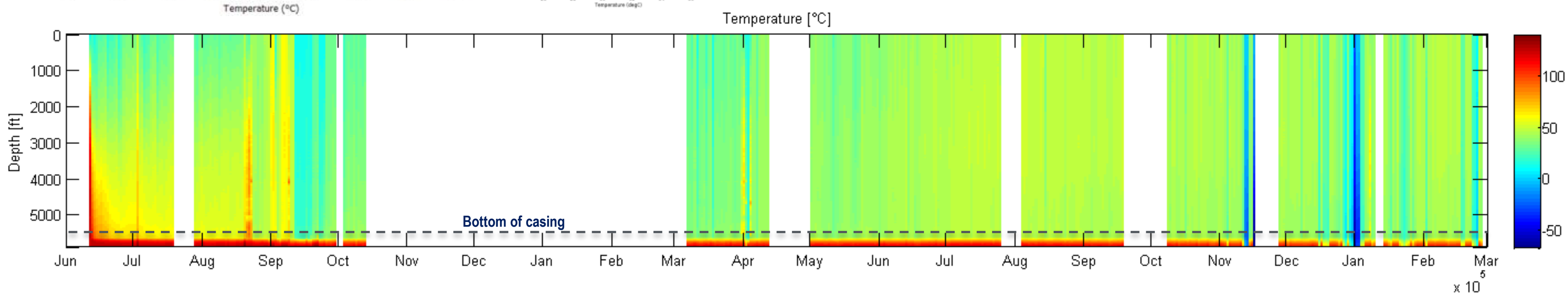


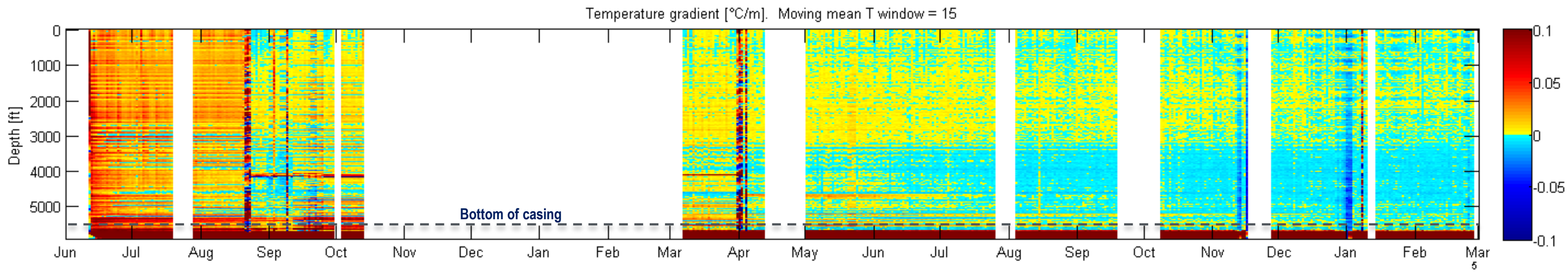
Temperature anomaly analysis





- Small-scale, high-resolution heat transport simulations to explain DTS temperature anomalies in cased portion of RRG-9
- Helped resolved concern that T anomaly suggested casing leak





Injection test analysis on the edge of precision, 2014 SULI student project

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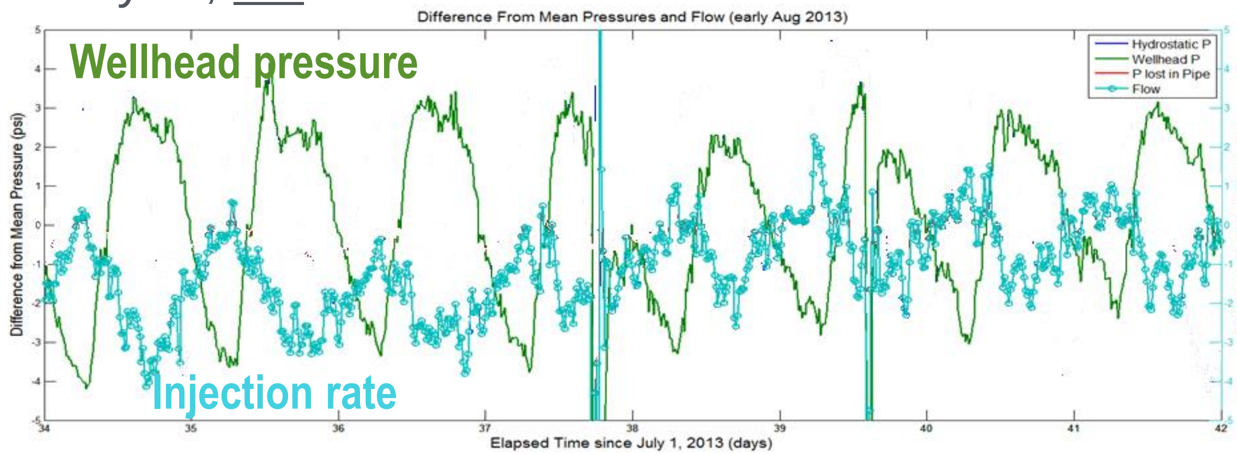
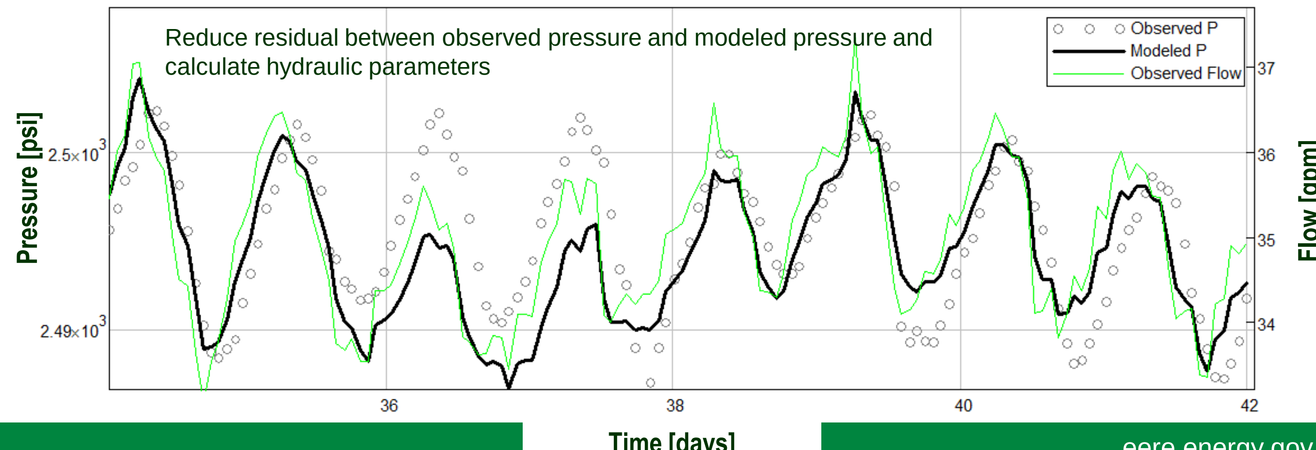
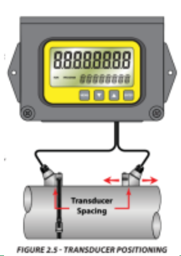
- Used DTS data to calculate precise bottom-hole pressure (BHP) (sensor failed)
- Corrected for T-dependent density & hydrostatic head, pressure loss via flow, …
- Wellhead flow and pressure data suggest diurnal fluctuation that could be used for transient pumping test analysis, <u>but</u>
- Plant, wellhead and calculated bottomhole pressure out of phase with flow rate variation
- Hypothesize uncompensated temperature effect in pressure sensor
- New BHP sensor 4/8/15







Permeability response to thermal effects

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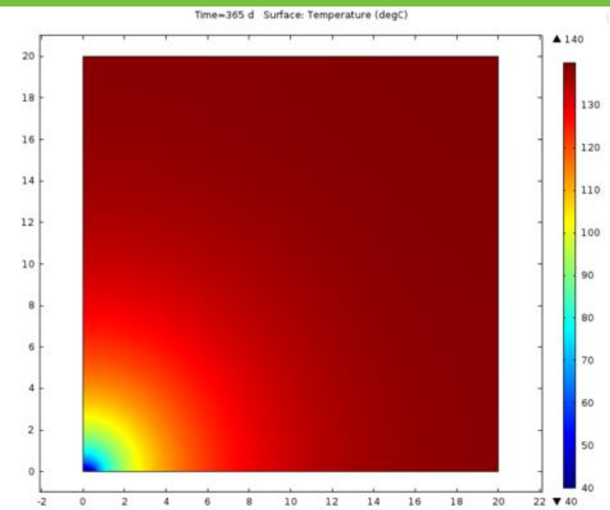
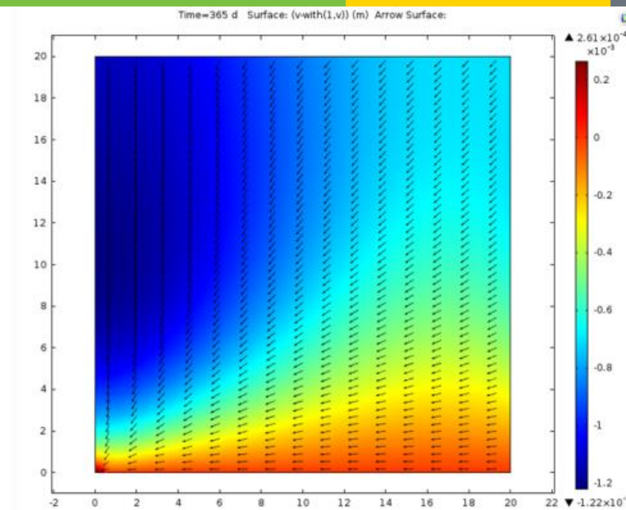
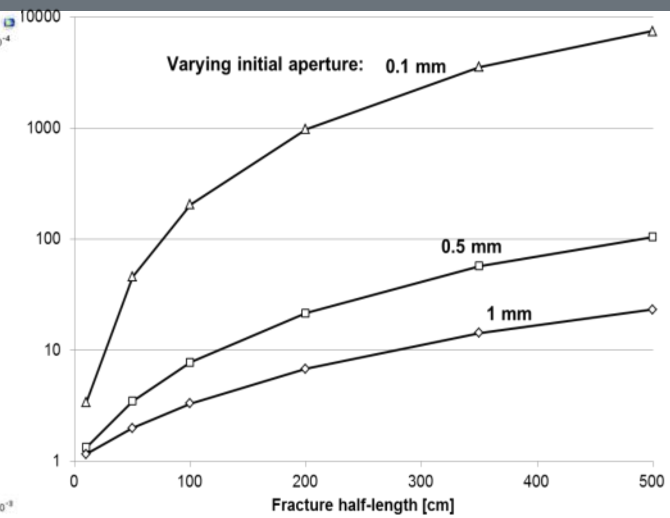
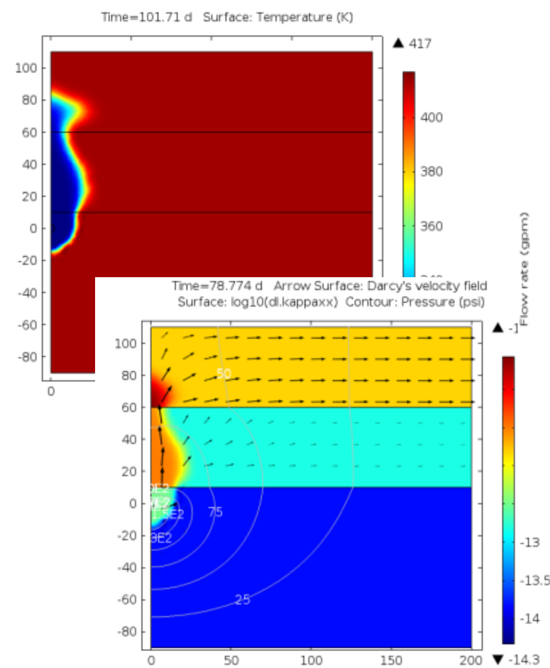
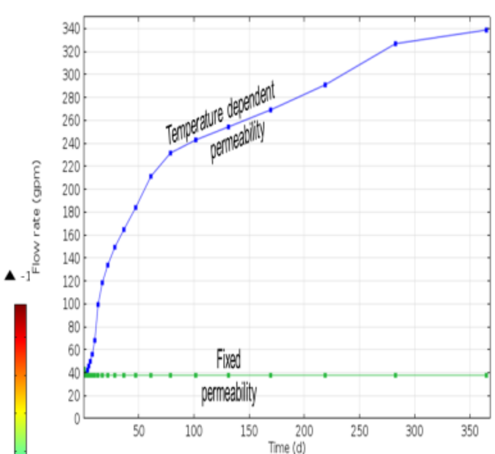






- Numerical simulations of discrete fracture response to thermal stimulation demonstrate k_{rel} dependence on unsupported fracture length & ΔT
- 2D simulations demonstrate how thermal effects can reproduce observed long-term evolution of injectivity





DEM simulations of stress and permeability response

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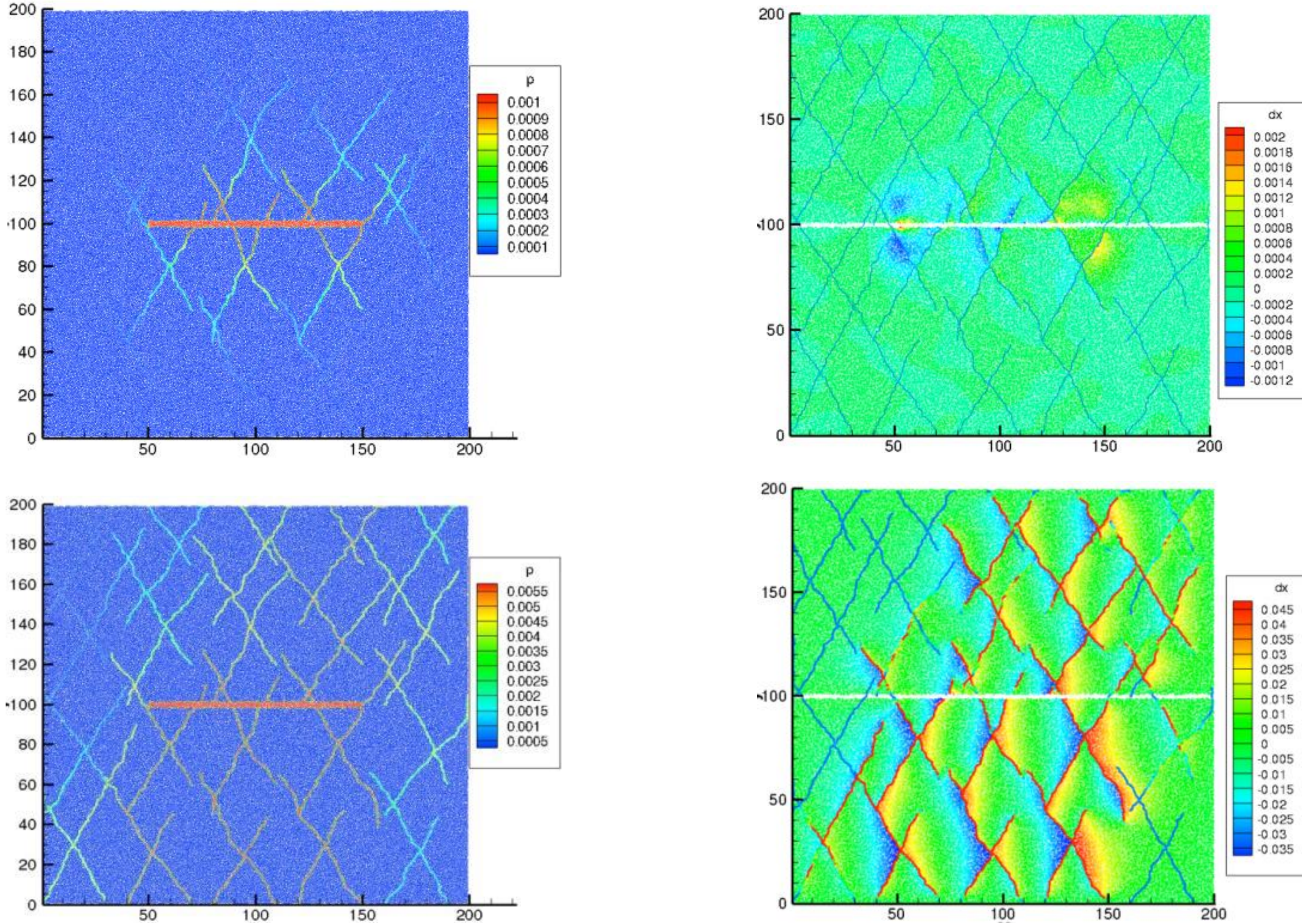
Fluid pressure

Horizontal displacement field
(& fracture network colored by permeability)

← Time ←

Shortly after injection start

Steady state



DEM simulations of stress and permeability response

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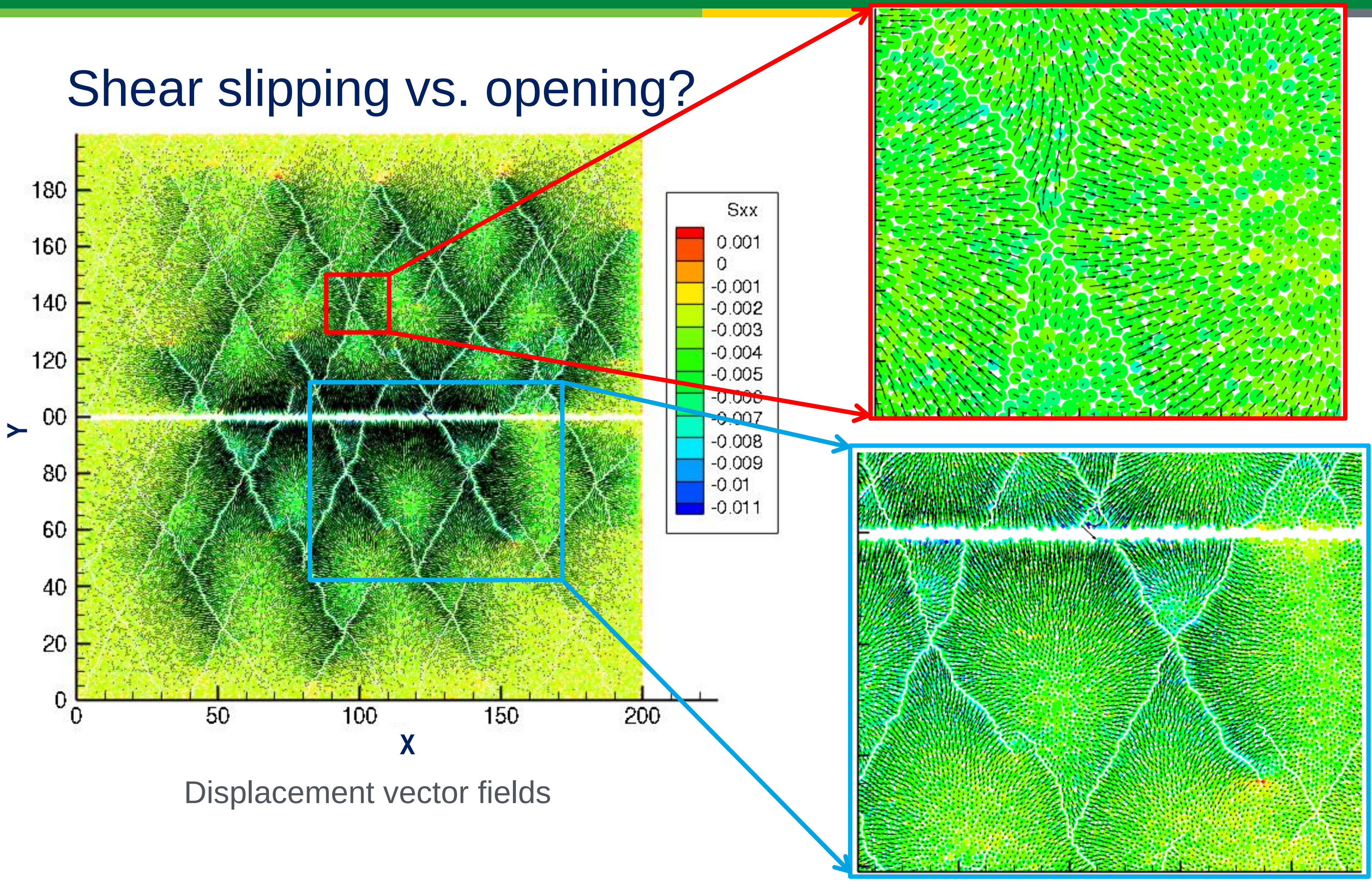
Shear slipping vs. opening?



Displacement vector fields

Accomplishments, Results and Progress

- Applied pumping test analysis methods to interpret injection test pressure / flow response
- Used numerical simulation of heat transport in a well to test hypotheses about temperature anomalies in well
- Made numerous improvements to FALCON for geothermal reservoir simulations
- Worked with EGI Ph.D. student to:
  - Develop FALCON modules that automate importing of FRACMAN-generated fracture networks
  - Develop reservoir scale models that can reproduce observed pressure/flow response
- Worked with SULI student to develop a well injection model to simplify point sources in FALCON
- Worked with SULI student to use DTS data to calculate precise bottomhole pressure and examine diurnal pressure/flow fluctuation
- Used discrete element fracture models, coupled to flow network model, to test hypotheses about shearing response to thermal and high-pressure stimulation
- Developed discrete fracture THM models, using procedure developed by Rutqvist (1998) to simulate elastic response of fractures to hydraulic jacking tests

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Quarterly reports	Reports describing model modifications, analyses, and simulation progress	Quarterly
Peer-reviewed manuscript on well hydraulics and measurements	Conference proceedings papers	February, 2015

Technical challenges

- Lack of measured response at other wells (pressure, flow, tracer return)
  - Pumping test analysis without observation wells
- Non-uniqueness in fitted models
  - eg. Constant flow at constant pressure after ~1.5 days
    - Nearby connection to higher permeability zone
    - Alteration to spherical flow regime, reflecting pressure diffusion into adjacent hydrogeologic units
    - Fracture opening; proximal drawdown decreases with pressure diffusion

Future Directions

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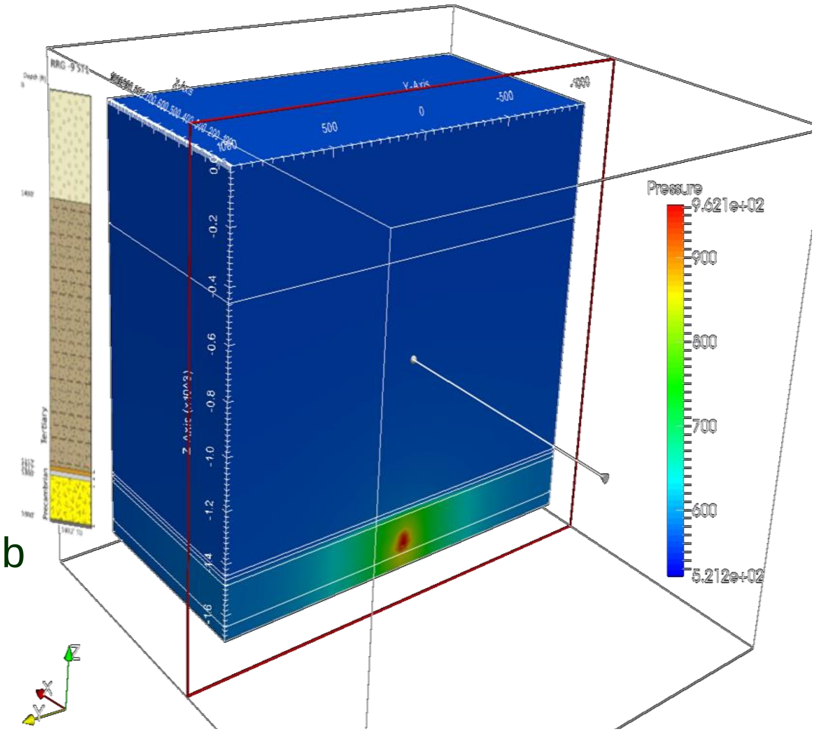
- Analyses, for hypothetical EGS and Raft River case study, provide improved understanding of reservoir response to well stimulation
- Continuing work focuses on 3D THM models and large-scale reservoir properties that could reproduce principle features of the observed hydraulic response
  - Use results of previous analyses to determine appropriate scale and features of 3D THM model
    - Summer, 2015: Work with EGI Ph.D. student, Jacob Bradford to develop alternative 3-D THM models, including single fracture zone response to thermal and high-pressure injection effects



- Continue FALCON simulations examining relationship between flow and thermal strain
- Continue DEM simulations exploring fracture distribution effect on stress/strain & flow

Milestone	Status & Expected Completion Date
Peer-reviewed manuscript on well hydraulics and measurements	May 1, 2015 (delayed from 2/28/15)
Peer-reviewed manuscript on reservoir modeling	July 31, 2015

Summary

- Simulations and analyses have supported Raft River stimulation effort
  - Design of stepped rate, hydraulic jacking, tests
  - Implications of temperature anomalies in cased well section
- Work to date focused on implications of well flow/pressure response
  - Calculated hydraulic properties and apparent response to stimulation
  - Apparent radial flow regime at <1-day timescale
  - Steady-state flow after ~1.5 days suggests fracture opening at 280 psi (~2 Mpa), or nearby high-k zone
  - No evidence of proximal impermeable boundary (Narrows zone)
  - Exploration of likely temperature-dependent injectivity response is consistent with range observed in thermal stimulation efforts
- Current work
  - Use discrete fracture THM model to simulate near-well fracture response
  - Apply THM with mechanics to simulate permeability response to effective fracture behavior
  - Reproduce long-term pressure/flow response with THM models