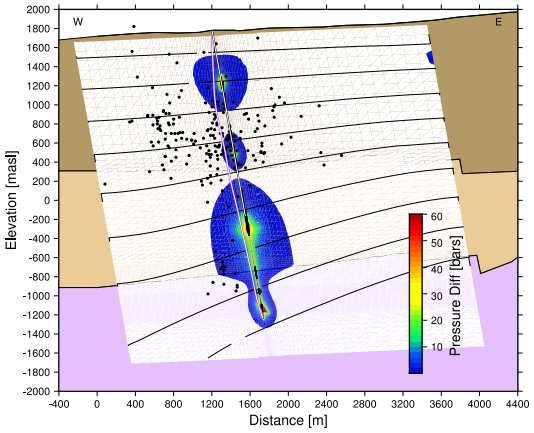
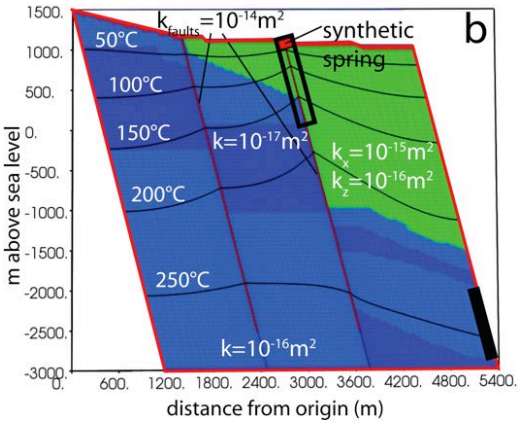
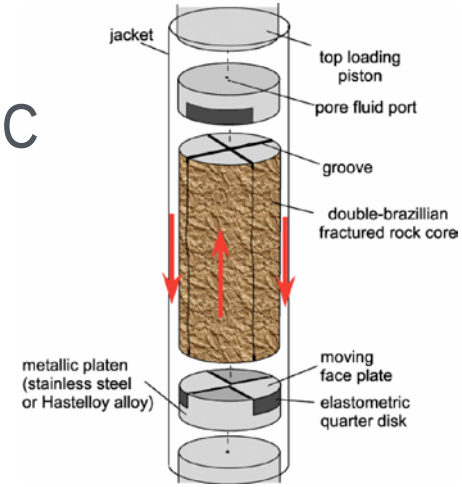
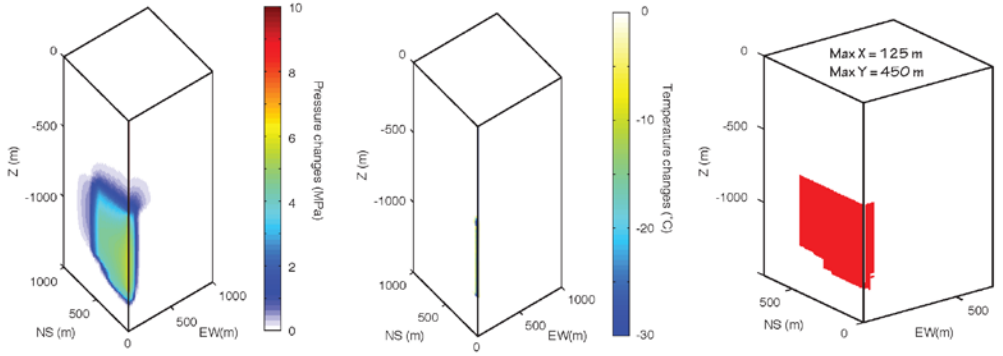




THMC





Coupled Thermal-Hydrological-Mechanical-Chemical Model And Experiments For Optimization Of Enhanced Geothermal System Development And Production: Evaluation of Stimulation at the Newberry Volcano EGS Demonstration Site through Natural Isotopic Reactive Tracers and Geochemical Investigation

Project Officer: Lauren Boyd Total Project Funding: $1.23M/634K

April 23 2013

Eric Sonnenthal

Lawrence Berkeley National Lab

Track 3

Relevance/Impact of Research

Objectives: *Develop a Novel Thermal-Hydrological-Mechanical-Chemical (THMC) Modeling Tool and Evaluate with Shear Fracture THMC Experiments (and test with isotopic data and modeling)*

- Principal barriers to EGS commercialization: Creating, sustaining and reducing the cost of reservoirs
  - *Coupled THMC models will directly address barriers to sustaining permeability in EGS and allow for analysis of the long-term effect of alternative methods for permeability creation. Effective injection schemes that evaluate chemical and mechanical effects on fracture permeability will allow for better techniques to reduce costs*
- Benefits: Will directly allow for the analysis and prediction of the sustainability of reservoirs that are deficient in water and/or those having low permeability, and allow for more effective heat extraction strategies. Code will reduce costs through reducing uncertainities introduced by simulating reservoir conditions/stimulation using separate uncoupled, TH, THM, and TC models
- Relevance: EGS require fracture generation as well as fluid injection to extract energy. Continued fluid injection, coupled to changes in the stress regime owing to temperature and pressure changes, leads to permeability changes via mechanical, chemical, and mechano-chemical processes.

Relevance/Impact of Research

- Innovative Aspects:
  - Integrated coupled THMC codes (in contrast to loosely coupled independent codes) were not previously available for analysis of dynamic fractured, multiphase, high-temperature conditions in EGS
  - Experiments to quantify mechanical, permeability, and chemical changes and fluid fluxes on shear fractures with fracture intersections under EGS-relevant conditions are new and directly applicable to EGS long-term sustainability
  - New mechanical models for multiple continua (fracture and rock matrix) will complement those developed for THC processes and allow for inclusion of fracture surface areas, and more accurate consideration of heat, fluid, and chemical fluxes in geothermal reservoirs
  - Combined experimental and modeling approaches allow for direct validation of modeling approaches and code capabilities, with insight into processes occurring in fractures shortly after stimulation and over longer time periods
  - Isotopic measurements modeling on the Newberry EGS will allow for quantitative constraints on THMC results, which has not been done in a fully integrated fashion before

Relevance/Impact of Research

- Impact to GTP Goals:

Goal: Model the reservoir conductivity at an EGS system demonstration

Progress toward meeting this goal:

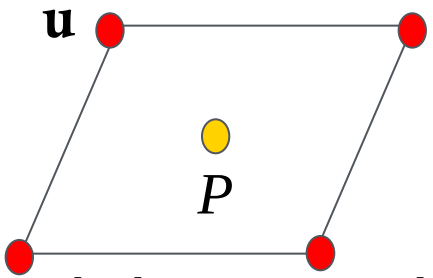
- The new code (TOUGHREACT-ROCMECH) is already being tested on Newberry EGS Demonstration Sites (Newberry)
- Simulations have also been performed in 3-D (Northwest Geysers)
- THC Simulations performed on 2-D cross-sections of Dixie Valley and Desert Peak, which helps in cross-confirmation of the conceptual models and approaches
- Isotopic data from Newberry will help constrain the effective fracture surface area and the rates of reaction leading to permeability changes over longer time periods
- Simulations of Sr and Rb isotopic evolution during water rock-interaction have been run on similar rhyolitic ash flow tuffs (unaltered and altered).

Scientific/Technical Approach

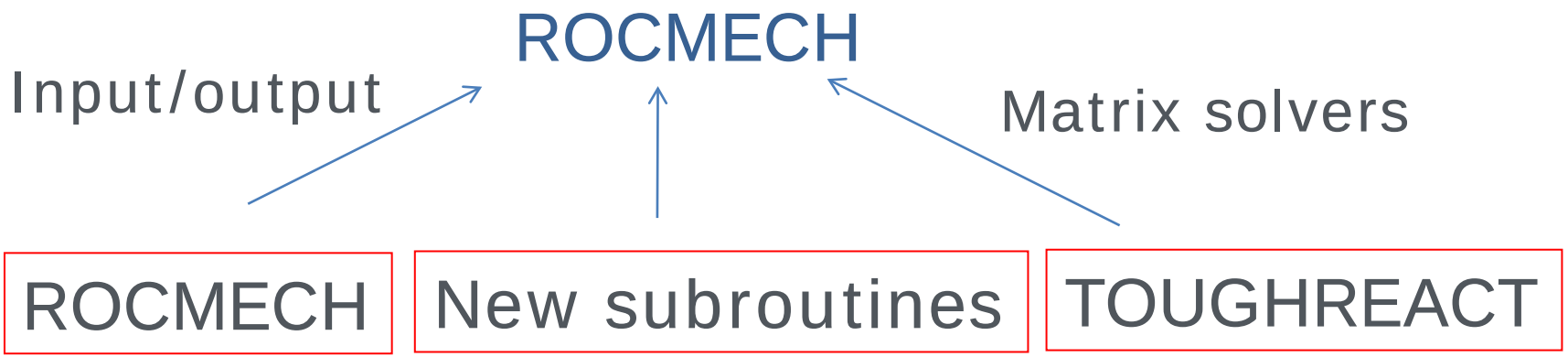
Approach/Key Issues

- Develop a simulator from the established THC code TOUGHREACT (Xu et al., 2006; 2011), and incorporate THM processes with added capabilities equivalent to those found in FLAC3D (Itasca)
- Incorporate small-scale processes in fractures through implementation of mechanistic crack growth and grain contact models for chemically induced subcritical crack growth and pressure solution, with porosity-permeability changes
- Conduct experiments to evaluate the long-term, coupled behavior of sheared fractures
- Validate the mechanistic THMC models of fracture aperture changes through comparison to experimental data on sheared fractures under stress under EGS-relevant temperature and chemical conditions
- Evaluate code on field-scale EGS demonstration projects
- Use geochemical and isotopic systems to evaluate the reaction rates and fracture surface areas after stimulation and over longer production time periods

ROCMECH

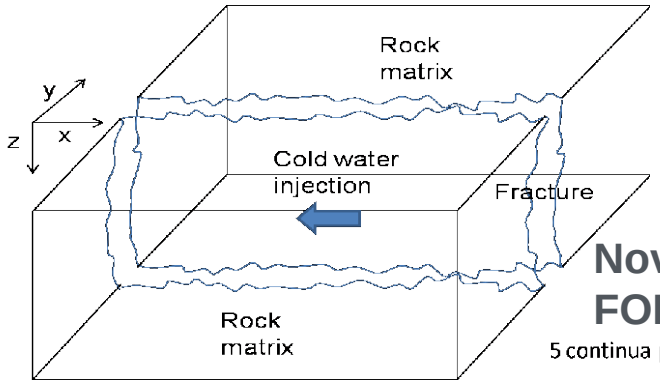


- Written in Fortran 90/95
- Employ finite element method
- Enjoy highly stable space discretization
  - Mixed finite-volume (flow)/finite-element method (mechanics)
- Apply the most recent method for coupled flow-mechanics
- Extension to multiple porosity system (MINC)



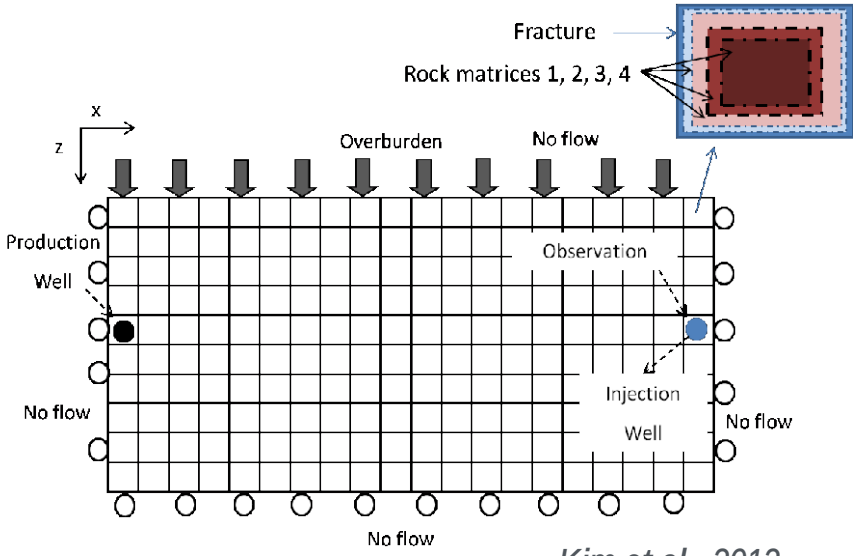
Scientific/Technical Approach

Sequential Implicit Algorithm Of Chemo-Thermo-Poro-Mechanics For Fractured Geothermal Reservoirs

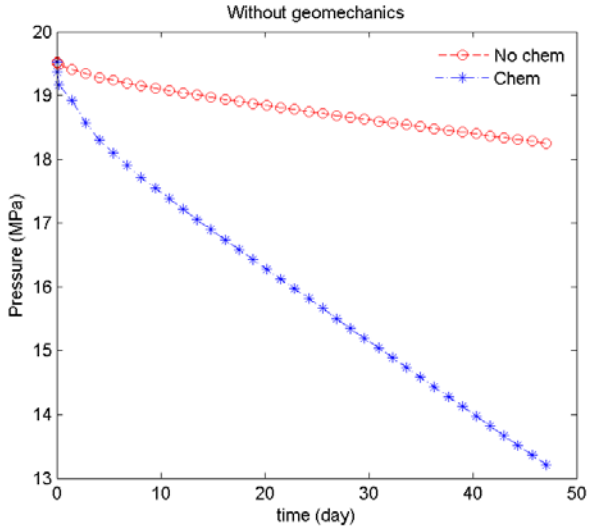


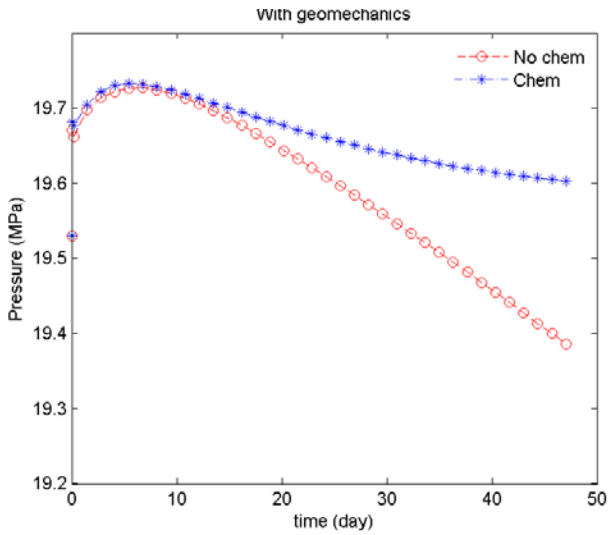
Novel MINC METHOD FOR THM

5 continua per gridblock



Kim et al., 2012





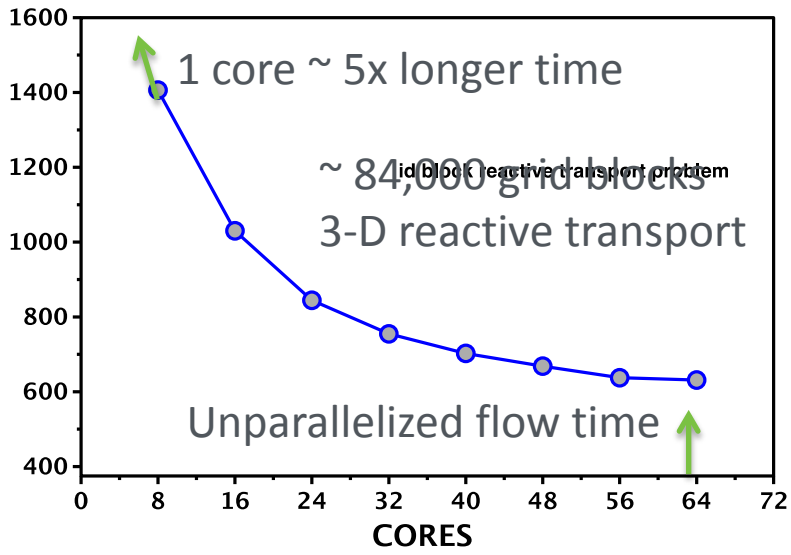
TOUGHREACT V2.2G HYBRID MPI-OPENMP THMC PARALLEL SIMULATOR

- Why: Large spatial scale of geothermal systems (> km) with the need for refined gridding around wells and faults
- Consideration of multiple interacting continua (MINC) for fractured rock
- Large temperature and pressure variations and strong coupling
- Many minerals, aqueous species, isotopes
- Current multicore multi-node clusters best suited for Hybrid MPI-OpenMP

OpenMP Speed Comparison (MacOS X 8-core)

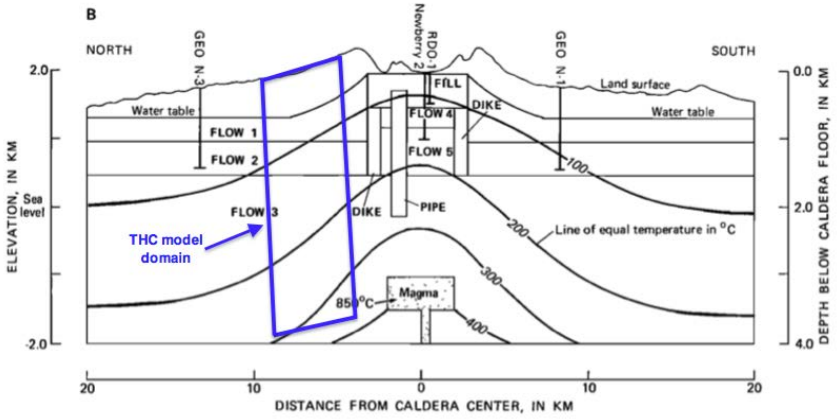
Test Problem	V2.086 1 Thread (sec)	V2.1 OMP 8 Threads (sec)	x Speedup
P4 EOS4	432.9	101.6	4.26
P5 ECO2N	41.26	11.42	3.61
P7 EOS9	30.10	11.96	2.52
P9 EOS9	145.2	86.20	1.68
P10 EOS1	204.7	31.82	6.43
P11 EOS4	1141.6	761.0	1.50
P12 ECO2N	4040.0	611.0	6.61

MPI-OpenMP on 64 Core Linux Cluster

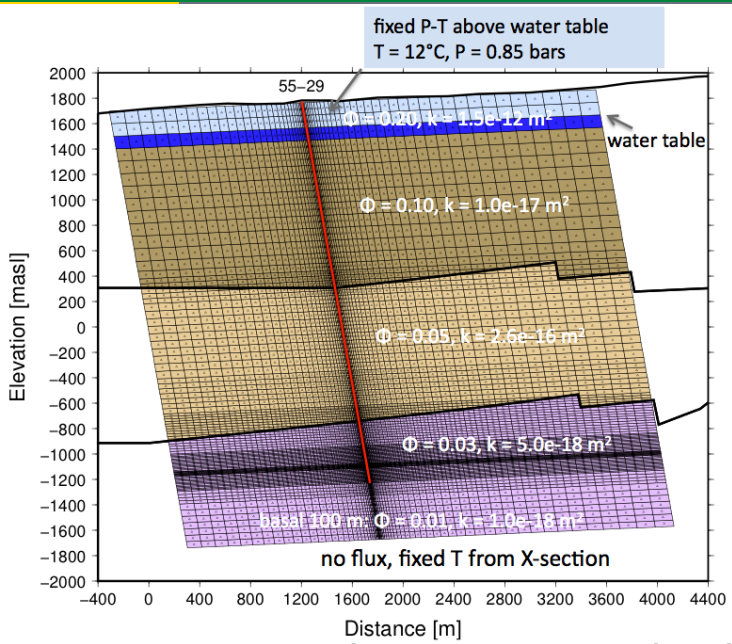


E. Sonnenthal, T. Smith, N. Miller, N. Spycher, T.Xu, in prep.

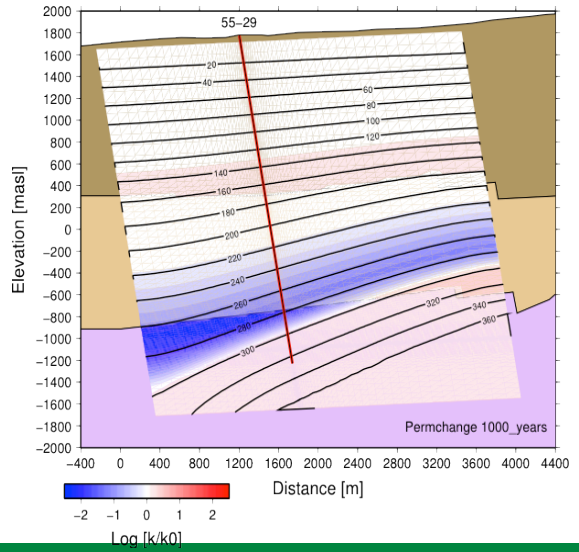
Newberry THMC Model

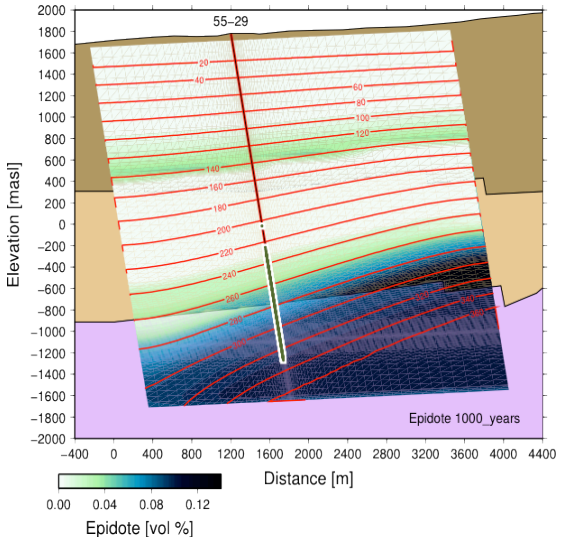


(after Sammel et al., 1988)

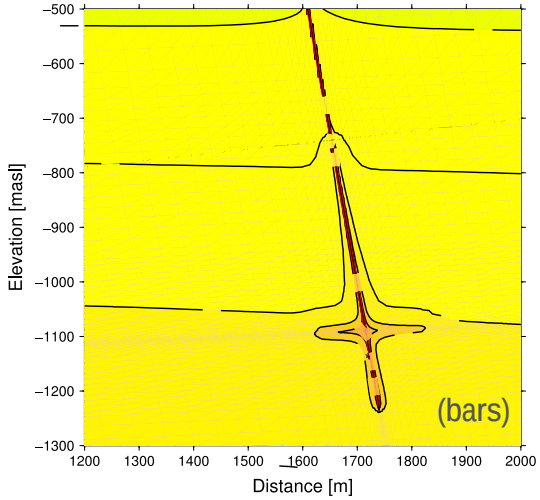


Native-State THC Model Simulations (Sonnenthal et al., 2012)



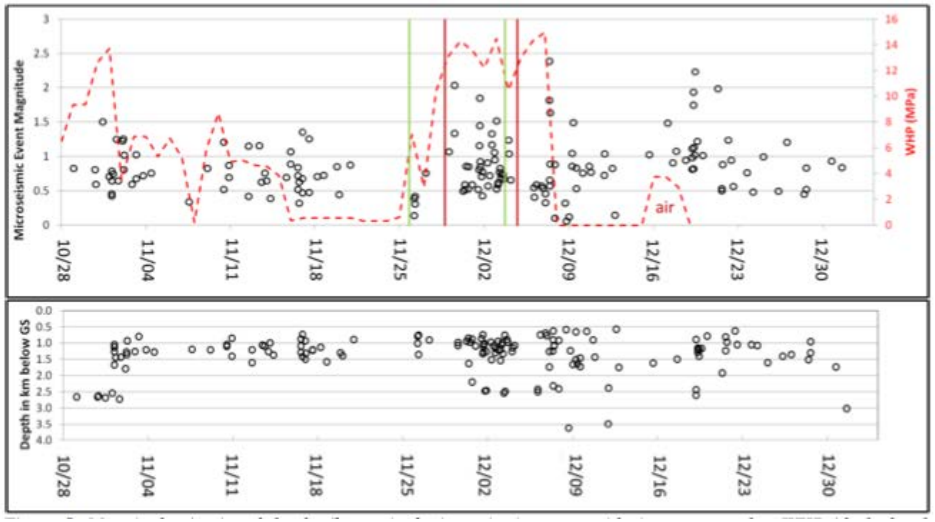


Pressure in Fracture Zone During Flow Test

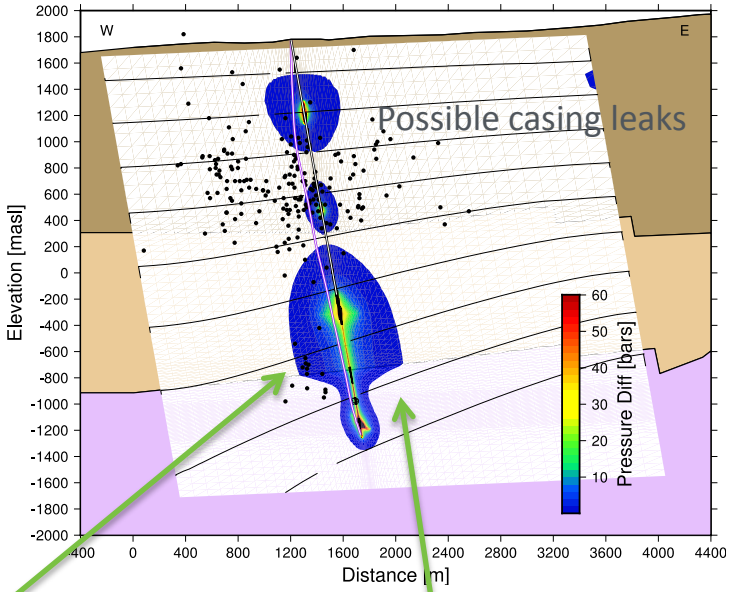


NEWBERRY VOLCANO 3-D THMC MODEL STIMULATION

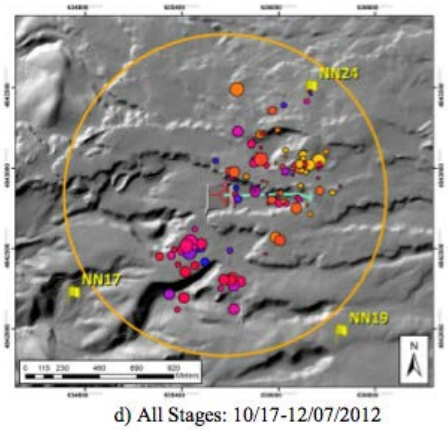
Wellhead Pressure and Microearthquakes

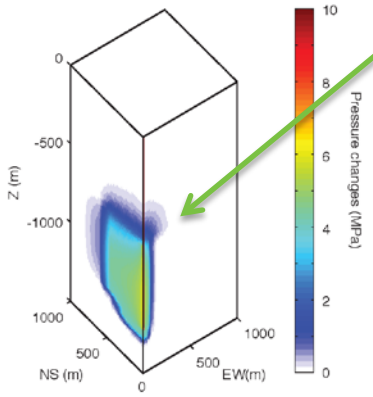


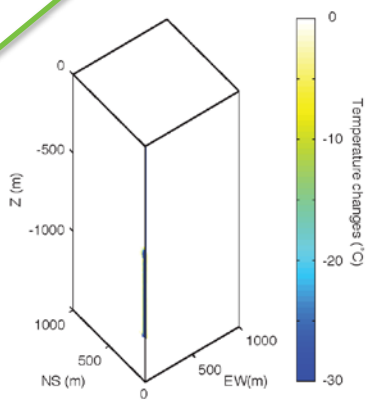
Pressure-Temp 3-D THC Model with MEQs

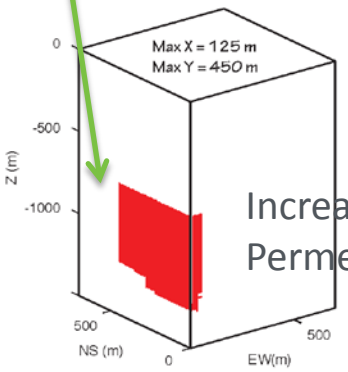


MEQ Locations: Cladouhos et al., 2013







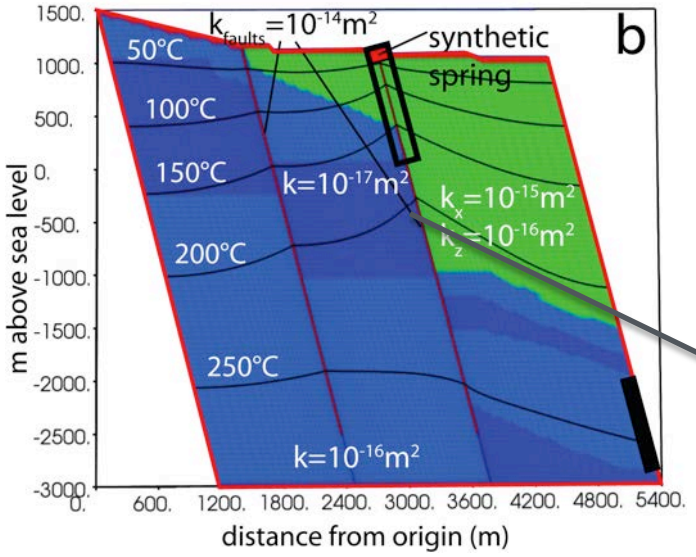


Increased Permeability

TOUGH_FLAC THM prediction of hydrosheared region - Rinaldi et al., 2012

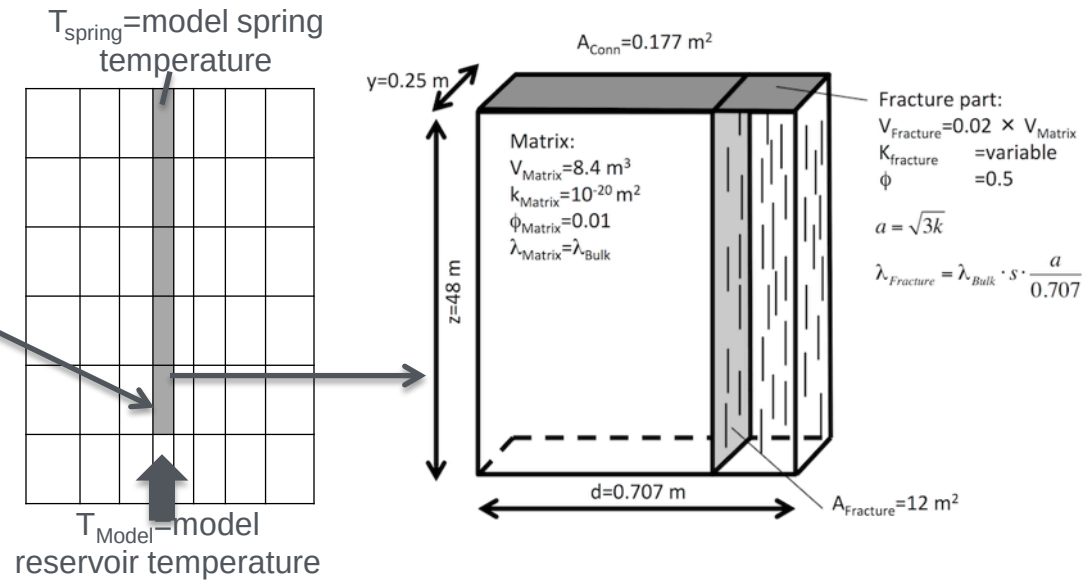
DIXIE VALLEY GEOTHERMAL AREA THC MODEL

- Dual continuum defined for central grid block column of eastern normal fault zone located > 0 m above sea level
- Simulation of thermal spring ("synthetic spring") being fed by a highly permeable but small scale fracture zone
- Variation of permeability k of dual continuum fracture to get different upflow velocities
- Simulations ran for k=10^{-14}, 10^{-12}, and 10^{-10} m^2



Wanner et al., 2013)

Model extension: dual continuum



Reactive Transport Model Developments/Accomplishments

- TOUGHREACT V2 Release June 2012 (http://esd.lbl.gov/research/projects/tough/software/toughreact.html)
- Development of high-performance TOUGHREACT V2.2G Hybrid MPI-OpenMP with improvements for geothermal system modeling (to be released in 2013)
- 2012 Director's Award For Exceptional Tech Transfer Achievement

Kim J., E. Sonnenthal, and J. Rutqvist, 2012. A Sequential Implicit Algorithm Of Chemo-Thermo-Poro-Mechanics For Fractured Geothermal Reservoirs . *Proceedings, TOUGH Symposium 2012*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Kim J., E. Sonnenthal, & J. Rutqvist, 2012. Formulation and sequential numerical algorithms of coupled fluid/heat flow and geomechanics for multiple porosity materials. *Int. J. Numer. Meth. Engng.* , doi: 10.1002/nme.4340.

Peiffer, L., Wanner, C., Spycher, N., Sonnenthal, E. L., and Kennedy, B. M., 2012, Revisited multicomponent chemical geothermometry: application to the Dixie Valley geothermal area: Mineralogical Magazine, v. 76, p. 2216.

Rinaldi A.P., J. Rutqvist, E.L. Sonnenthal, and T.T. Cladouhos, 2012. TOUGH-FLAC Coupled THM Modeling Of Proposed Stimulation At The Newberry Volcano EGS Demonstration. *Proceedings, TOUGH Symposium 2012*, Lawrence Berkeley National Laboratory, Berkeley, CA.

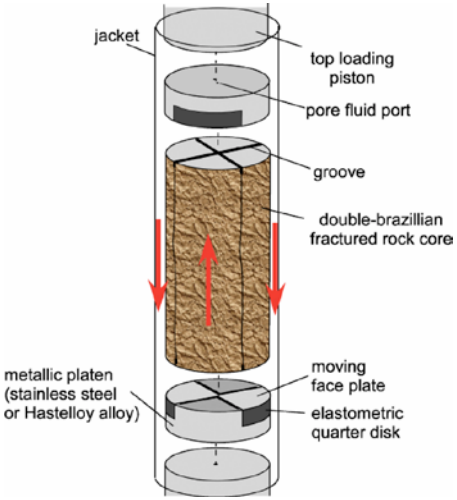
Sonnenthal E., N. Spycher, O. Callahan, T. Cladouhos, and S. Petty. A thermal-hydrological-chemical model for the Enhanced Geothermal System Demonstration Project at Newberry Volcano, Oregon., 2012. Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30 - February 1, 2012 SGP-TR-194.

Wanner, C., Peiffer, L., Sonnenthal, E. L., Spycher, N., Iovenitti, J., and Kennedy, B. M., in press, On the use of chemical geothermometry: A reactive transport modeling study of the Dixie Valley geothermal area: Procedia Earth and Planetary Science.

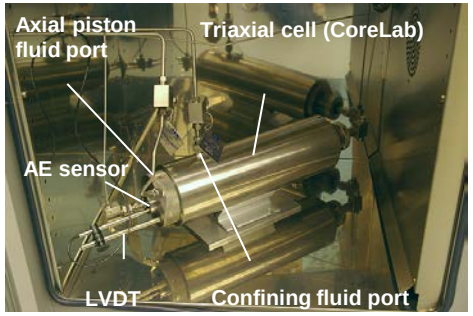
Wanner, C., Peiffer, L., Spycher, N., Sonnenthal, E. L., Iovenitti, J., and Kennedy, B. M., Constraining chemical geothermometry with reactive transport models: An example study of the Dixie Valley geothermal area: Abstracts AGU Fall Meeting 2012.

Wanner, C., Peiffer, L., Spycher, N., Sonnenthal, E. L., Sainsbury, J., Iovenitti, J., and Kennedy, B. M., Assessing thermo-hydrodynamic-chemical processes at the Dixie Valley geothermal area: a reactive transport modeling approach: Proceedings, Thirty-Eighth Workshop on geothermal reservoir engineering, Stanford University, Stanford, Ca, February 11-13, 2013.

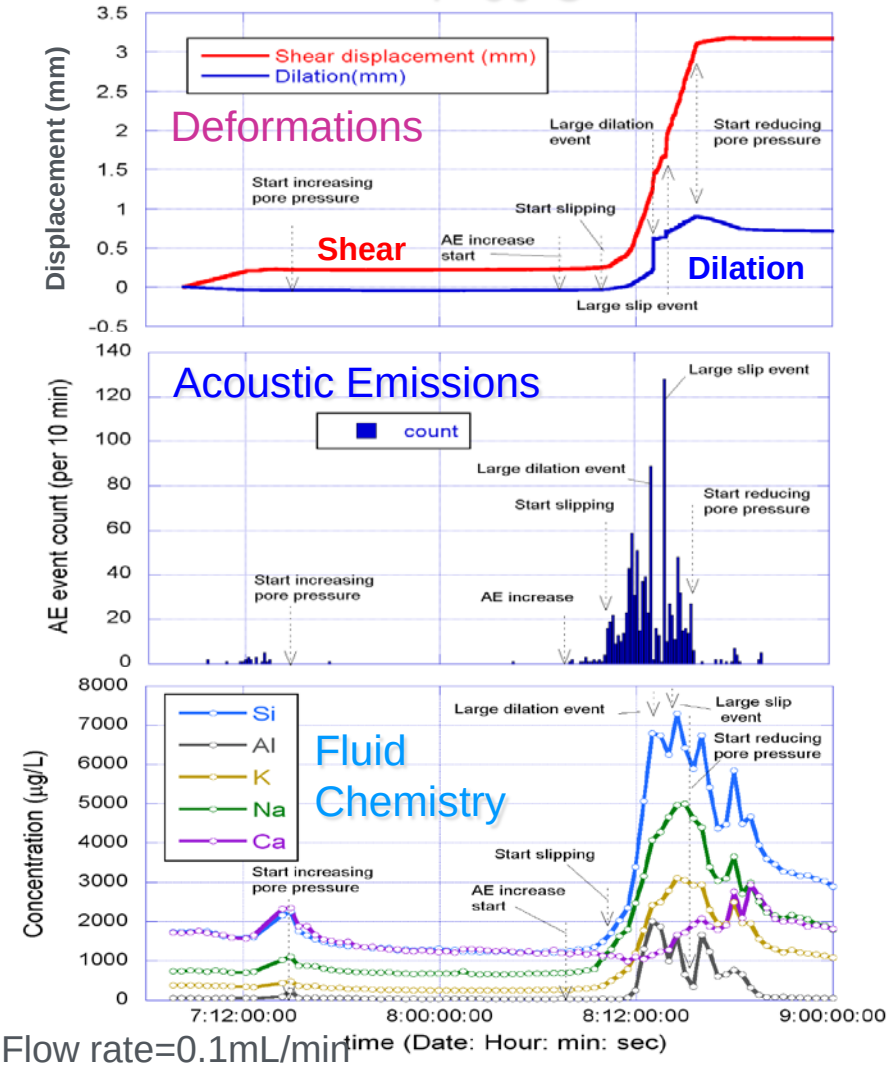
Experimental Investigation of THMC behavior of sheared fractures



A unique direct shear experimental setup was developed. Multi-physical measurements were conducted on granite fractures during their destabilization



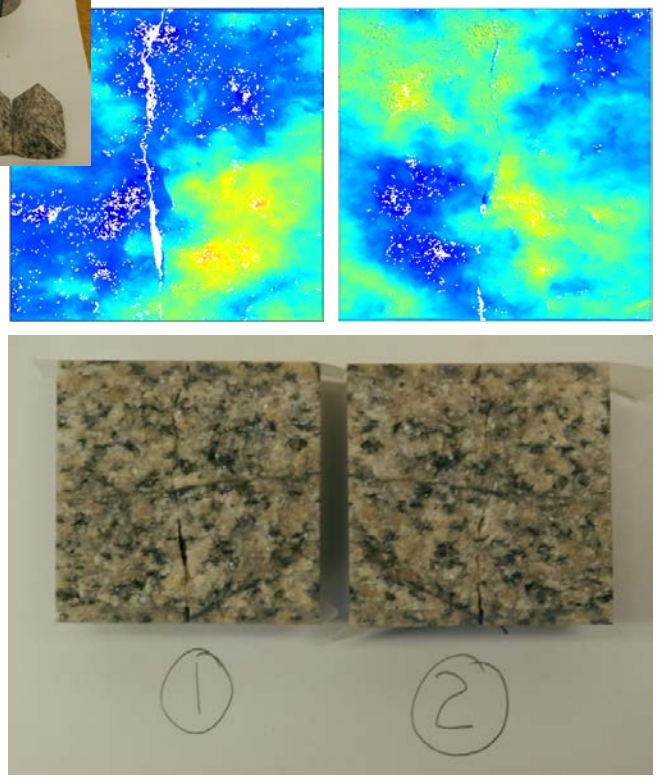
T=60ºC



Flow rate=0.1mL/min

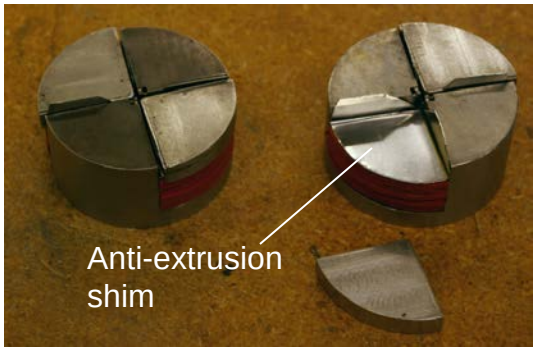
Fractured granite cores (Stripa)

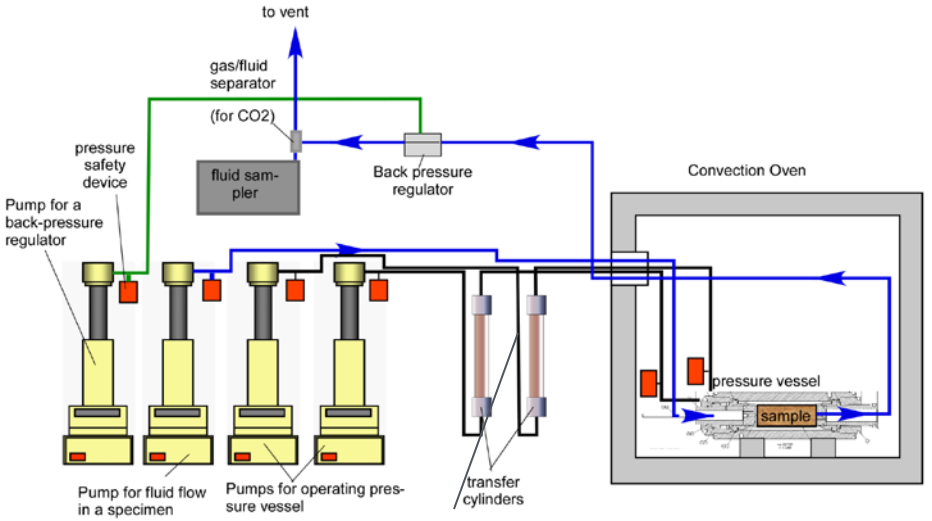
- Surface profile measurements before and after the shear experiment
- Nanovea PS-50 used (optical profilometer)

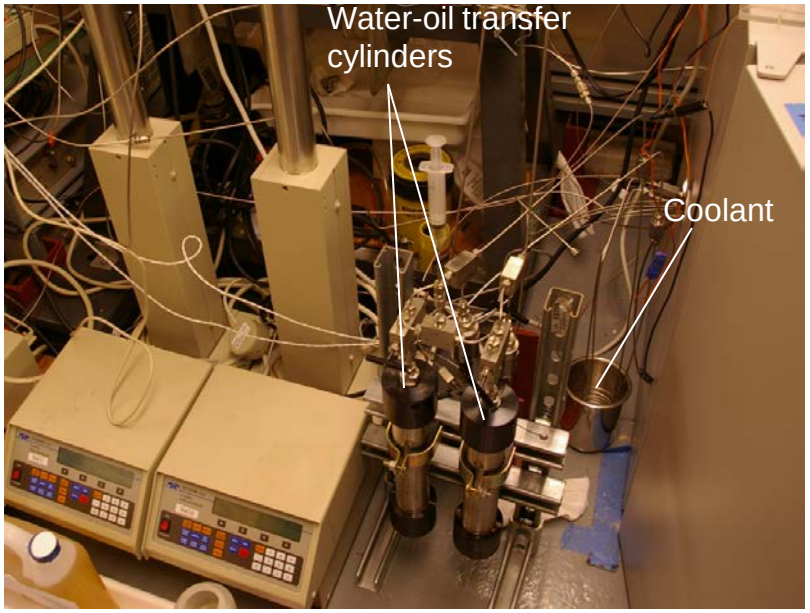


High-Temperature Experiments in Progress (100–200ºC)

- Currently 150 ºC tests in progress
- High-T acoustic emission sensors and LVDT (displacement sensor) used
- Shear platens re-designed to avoid elastomer (rubber) extrusion







Future Directions

Milestone or Go/No-Go	Status & Expected Completion Date
3.3. Complete THMC shear fracture experiment. Measurement of fracture permeability differences and aqueous chemistry with and without shear stress.	Experimental set-up complete. Experiment started in 3/2013 on granitic rock but controller failed. Will restart experiment in Spring 2013. Expected completion 6/2013.
3.2. Evaluate Toughreact-ROCMECH on field geothermal problem.	Preliminary test on Newberry EGS, but will make full THMC test using TOUGH-FLAC THM and TOUGHREACT THC simulations as a basis for detailed evaluation. 9/30/2013
1.a Collection of Newberry waters for isotopic analyses. Go-No go: If water samples are not collected from 55-29, will use funds to try different methods of sampling and/or try to sample other wells.	First stage of sampling expected completion 7/2013.

Summary Slide

Understanding and modeling coupled THMC processes are necessary to design and cost-effectively develop EGS resources

In this project we are developing a high performance THMC simulator TOUGHREACT-ROCMECH that can treat thermal, hydrological, mechanical, and chemical processes for multiphase systems in fractured rock, using:

- **New multiple continuum approaches for thermo-poro-elastic processes in fractured rock**
- **State-of-the art reactive transport model with thermodynamic-kinetic controls on mineral-water-gas reactions, mineral solid solutions, and isotopic fractionation for stable and radiogenic systems**
- **Hybrid OpenMP-MPI parallelism for accelerated computations on workstations and large clusters**
- **Improved and tested thermodynamic databases for geothermal systems**
- **THM Cross-comparison (TOUGH-FLAC)**

Highly resolved 2-D and 3-D simulations of Newberry EGS are supporting the AltaRock EGS Demonstration EGS Project and furthering the testing of THC and THMC process models embedded in TOUGHREACT-ROCMECH. Isotopic Data from Newberry EGS will allow for constraints on the initial rock properties and their evolutions

Novel Flow-through hydroshear experiments are being performed at elevated temperatures which monitor geochemical and hydrological changes and geophysical signatures during a pressure induced shear event. Small-scale processes and microseismicity associated with hydroshearing and the concomitant chemical and isotopic response will allow for a much better understanding of the full THMC responses at the fracture-scale during stimulation

Project Management

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- The purpose of this slide is to provide some context for evaluating your project.
- Please prepare one overview slide containing the following information:

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
9/30/2009	9/30/2012	9/30/2009	1/31/2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$512	$0	$1,230	$1,230	$1,230	$0

  - Leveraging with Newberry Demonstration Project and a DOE FOA project on model development for nontraditional isotopes
  - Closely integrated and coordinated with AltaRock, Inc. for Newberry EGS Demonstration Project
  - Integration with Penn State THMC EGS project
  - Coordination with AltaRock and Calpine
- High-temperature experiments delayed due to controller breakdown.

Project Management

Timeline:

	Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date		
	10/1/2012	9/30/2014	1/1/2013	9/30/2014		

Budget:

	Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Est. Value of Work Completed to Date	Funding needed to Complete Work
	$640	$0	$240	$10	$160	$630

- Resources primarily to be spent on obtaining samples and performing necessary chemical and isotopic measurements
  - Leveraging with Newberry Demonstration Project and a DOE FOA project on model development for nontraditional isotopes
  - Closely integrated and coordinated with AltaRock, Inc. for Newberry EGS Demonstration Project
- Water samples from the Newberry stimulation could not be collected yet, but work is progressing on groundwater samples