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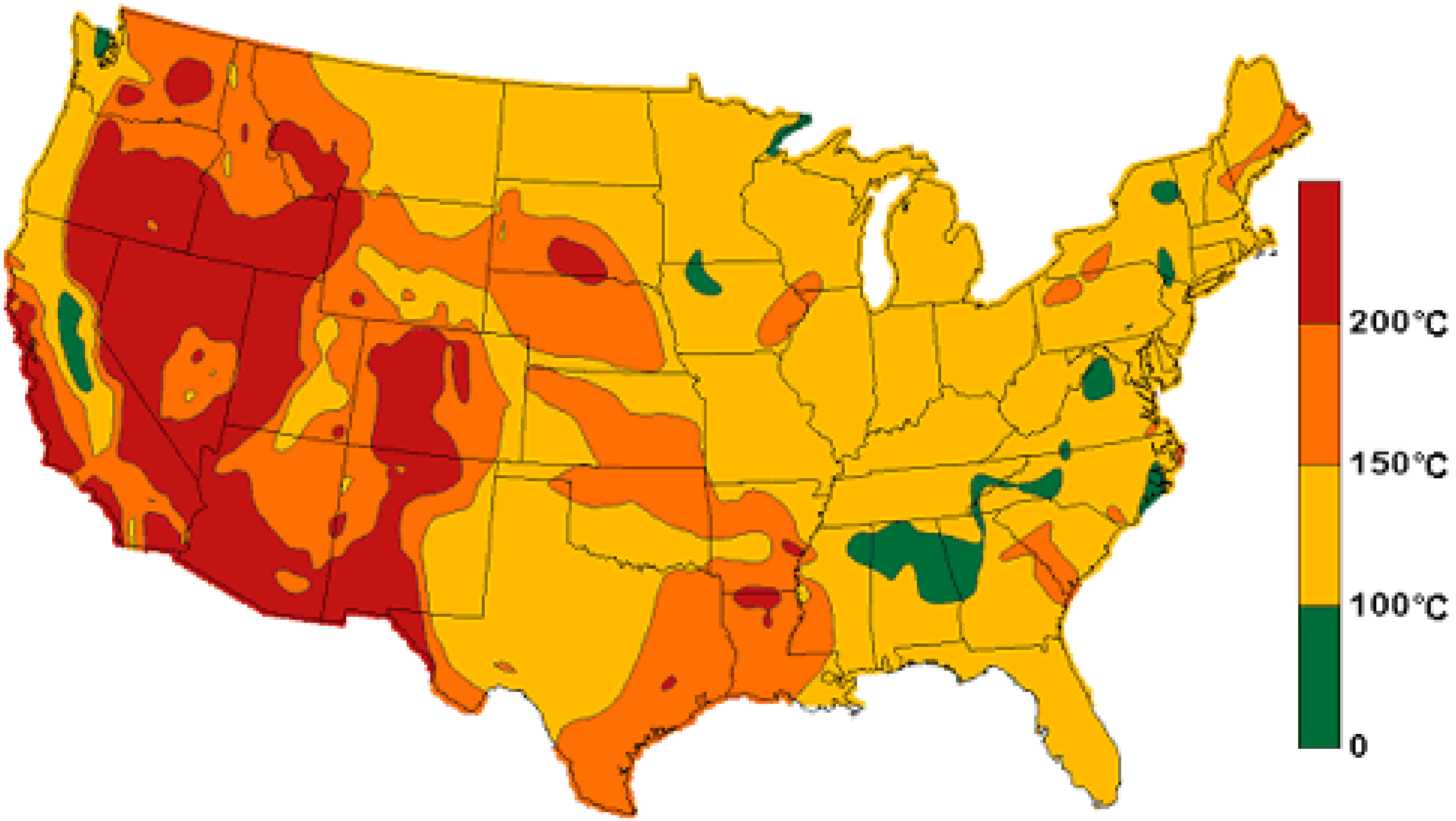


Development of Advanced Thermal-Hydrological-Mechanical-Chemical (THMC) Modeling Capabilities for Enhanced Geothermal Systems

Project Officer: Dr. Bill Vandermeer

Total Project Funding: $1,633,493

April 24, 2013

Dr. Yu-Shu Wu

Colorado School of Mines

DE-EE0002762

Overview

- Timeline

Start Date	End Date	Complete
01/01/10	12/31/2013	90%

- Budget

Contributor	Fund
Department of Energy (DOE)	$1,191,893
Computer Modeling Group Ltd. (CMG)	$441,600
Total	**$1,633,493**

- Partners

Colorado School of Mines

Lawrence Berkeley National Laboratory

Computer Modeling Group Ltd.

Relevance/Impact of Research

- The reservoir simulator developed from this project is among the first rigorous fully couple hydro-thermal-mechanical-chemical (THMC) reservoir simulator **in public domain**.
- This simulator will substantially enhance our ability to characterize EGS systems and provide practical approaches to assess the following:
  - Long-term performance
  - Optimum design
  - Operation strategies, and
  - Commercial feasibility

Project Objectives

- **Develop a general framework** for effective flow of water, steam and heat in in porous and fractured geothermal formations
- **Develop a computational module** for handling coupled effects of pressure, temperature, and induced rock deformations
- **Develop a reliable model** of heat transfer and fluid flow in fractured rocks
- **Develop a chemical reaction module** to include important chemical reactions in EGS
- **Develop an efficient parallel computing** methodology for simulation purposes
- **Apply the EGS simulator** to laboratory and field data of geothermal reservoirs.

General framework: Integral finite differences

$$\frac{d}{dt}\int_{V_n} \mathbf{M}\ dV_n = \int_{\Gamma_n} \mathbf{F} \bullet \mathbf{n} d\Gamma_n + \int_{V_n} q\ dV_n$$

Mass balance equation

for Component κ

$$M^{\kappa} = \sum_{\beta} \phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}$$

$$F_{\beta}^{\kappa} = \sum_{\beta} X_{\beta}^{\kappa} v_{\beta}$$

$$v_{\beta} = -k \frac{k_{r\beta} \rho_{\beta}}{\mu_{\beta}} (\nabla P_{\beta} - \rho_{\beta} \mathbf{g})$$

Energy balance equation

$$M^{h} = (1-\phi)\rho_R C_R T + \phi \sum_{\beta} S_{\beta} \rho_{\beta} u_{\beta}$$

$$F^{h} = -\left[(1-\phi)K_R + \phi \sum_{\beta} S_{\beta} K_{\beta}\right] \nabla T + f_{\sigma} \sigma_0 \nabla T^4 + \sum_{\beta} h_{\beta} F_{\beta}$$

Force balance equation

$$M = 0$$

$$F = \frac{3(1-\nu)}{(1+\nu)} \nabla \tau_m + F_b - \frac{2(1-2\nu)}{(1+\nu)} \nabla \left[\sum_j \alpha_j p_j + 3\beta K \omega_j T_j\right]$$

Rock deformation module

- Fully-coupled geomechanics and flow modules based on poro-thermo-elastic assumptions

- Force balance equation:

$$\int_{\Gamma_n} \left[\frac{3(1-\nu)}{(1+\nu)} \nabla \tau_m + F_b - \frac{2(1-2\nu)}{(1+\nu)} \nabla \sum_j \left(\alpha_j p_j + 3\beta K \omega_j T_j \right) \right] \bullet \mathbf{n} d\Gamma_n = 0$$

$$K\varepsilon_v = \tau_m - \sum_j \left(\alpha_j p_j + 3\beta K \omega_j \left(T_j - T_{ref} \right) \right)$$

Rock deformation module

- Stress-sensitive hydraulic properties
  - Four correlations for porosity-stresses and
  - Four correlations for permeability-stresses are implemented

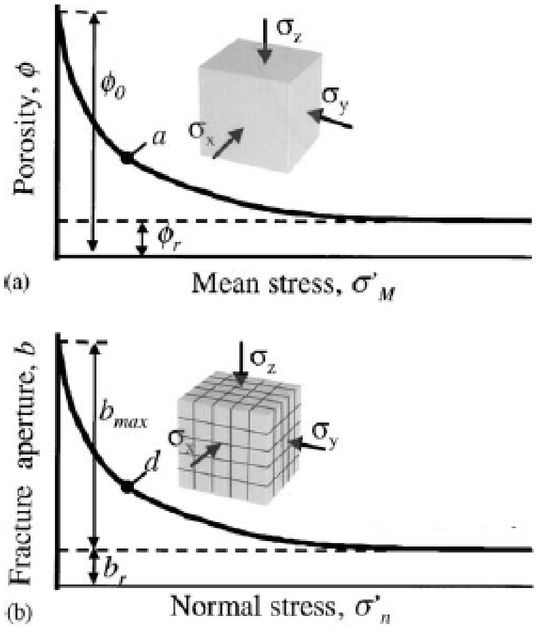
For example:

$$\tau_m' = \tau_m - \alpha p$$

$$\phi = \phi\left(\tau_m'\right) \qquad \phi_f = \phi_f\left(\tau_m'\right)$$

$$k = k\left(\tau_m'\right) \qquad k_{fi} = k_{fi}\left(\tau_m'\right)$$

$$Pc = Pc_0\left(\frac{\sqrt{k_i/\phi_i}}{\sqrt{k/\phi}}\right)$$



Rutqvist et al. 2002; Rutqvist, J. Y.S Wu, C.F. Tsang, and G.S. Bodvarsson, A modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock, *International Journal of Rock Mechanics and Mining Sciences,* Vol. 39, pp.429-442, 2002.

Chemical reaction module

- Aqueous-based reservoir stimulation is likely to promote dissolution of some rock minerals, while precipitating others, and lead to large impact on the permeability of the fracture network
- Mineral dissolution and precipitation are considered under kinetic conditions and The temperature dependence of the reaction rate constant can be expressed via an Arrhenius equation
- **Transport equations:** Mass balance (transport) equations for chemical components can be expressed as:

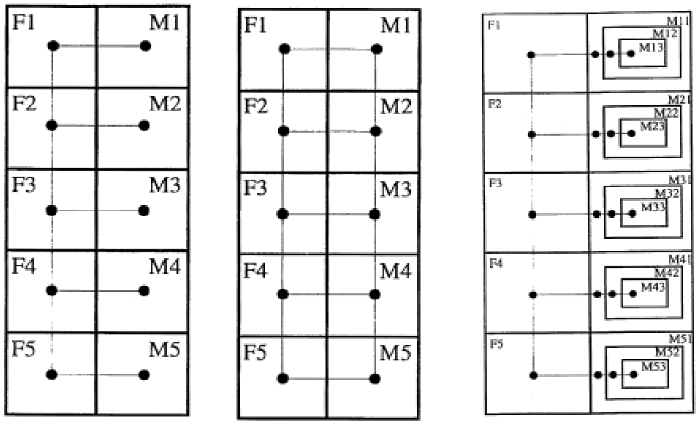
$$\frac{d}{dt}\int_{V_n} \mathbf{M}^{\kappa} dV_n = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma_n + \int_{V_n} q^{\kappa} dV_n + \int_{V_n} R^{\kappa} dV_n$$

where κ is chemical component index, such as Ca^{2+}, SiO_2(aq), and R is mass transfer from solid phases such as calcite and silica mineral dissolution and precipitation.

- Chemical reactions are considered as secondary equations

Fracture module

- Generalized dual-continuum methodology: treats fracture and matrix flow and interactions using a multi-continuum numerical approach



- The Approach can be applied for
  - Discrete fracture i.e. hydraulic fracture (man made) and faults
  - Fracture network or naturally fractured reservoirs

Parallel computing module

- Advanced parallel simulation scheme has been developed and implemented into TOUGH2-EGS simulator.

- Considering the highly nonlinear nature of the coupled processes as well as the large number of mass/chemical components, involved in multiphase fluid and heat flow in EGS systems, efficient parallel computation is an essential step for any realistic field-scale application of reservoir modeling tools (Zhang et al. 2001a, Zhang and Wu, 2006).

- The parallel simulation capability has been built by taking advantage in rapid advance in computer and computational sciences, as well as high-performance reservoir simulation technology (Wu et al. 2002; Zhang et al. 2008).

Accomplishments, Results and Progress

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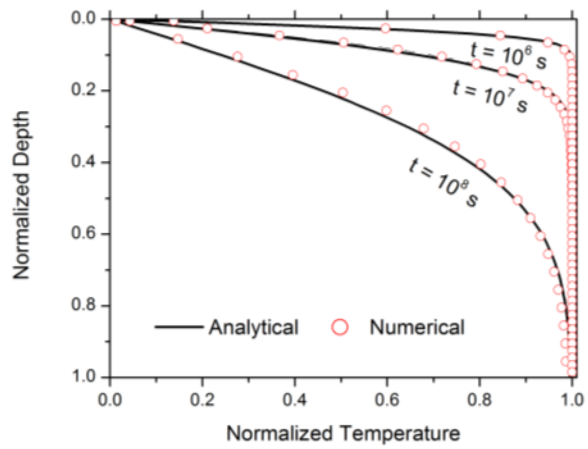
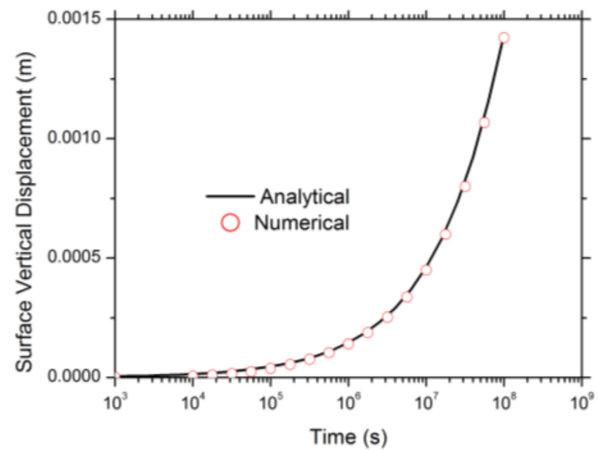
- Developed simulators
  - TOUGH2-EGS (THMC for single CPU)
  - TOUGH2-EGS-MP (THM for multiple CPUs)
- Published seven conference papers

Original Planned Milestone	Technical Accomplishment	Date Completed
Verify the developed simulators against:		
• Analytical solutions	Completed	Q2 2011
• Commercial simulator	Completed	Q3 2011
• Published simulation study	Completed	Q1 2012
• Field data	Completed	Q4 2012
Public training	**June 2-3, 2013**	-

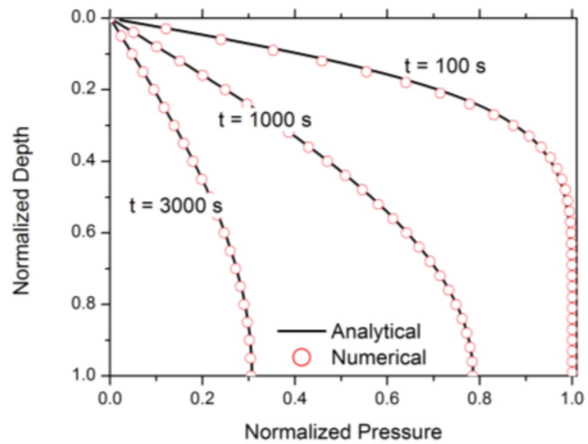
Verification: Against analytical solutions

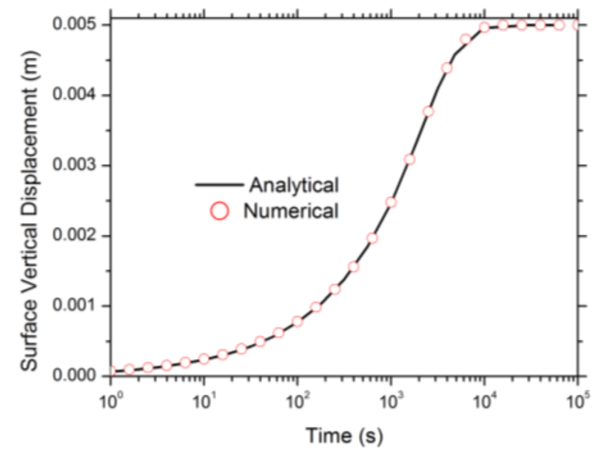
1-D Heat Conduction in Deformable Media (Jaeger et al., 2007)



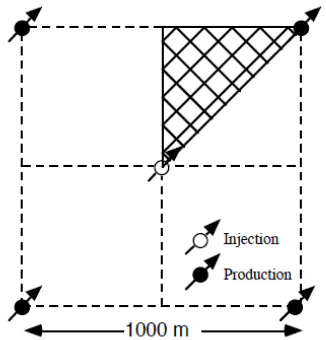


1-D Consolidation (Terzaghi et al., 1996)

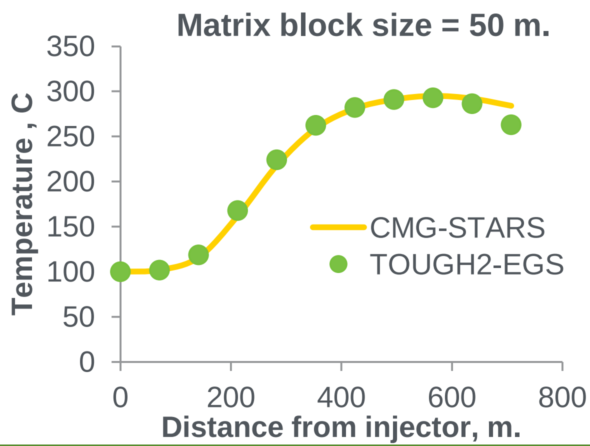


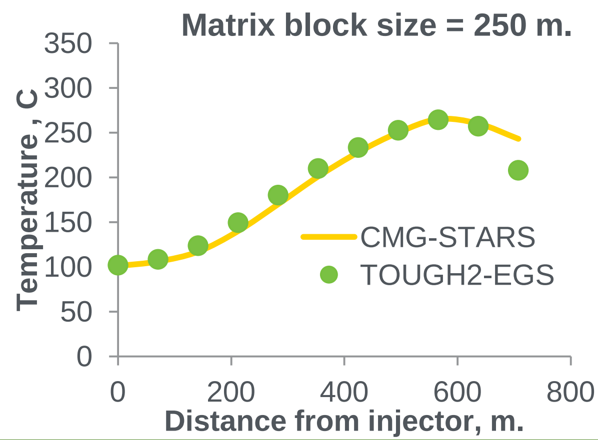


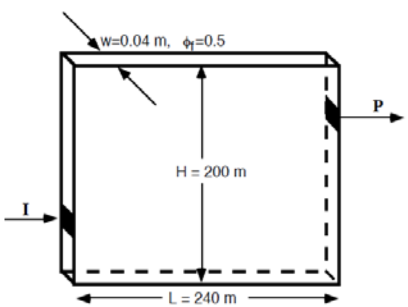
Verification: Against CMG-STAR (commercial simulator)



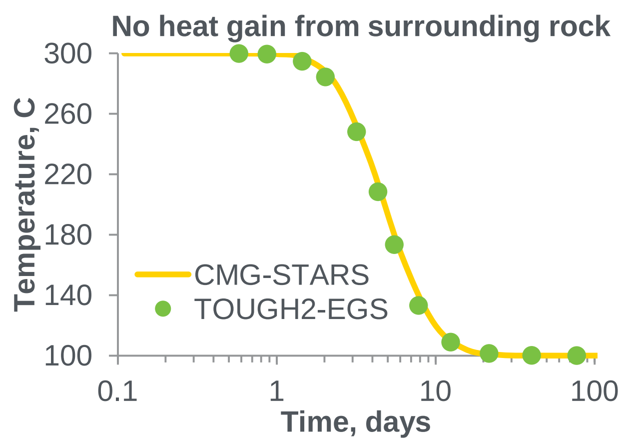
Five-spot Geothermal Production/Injection

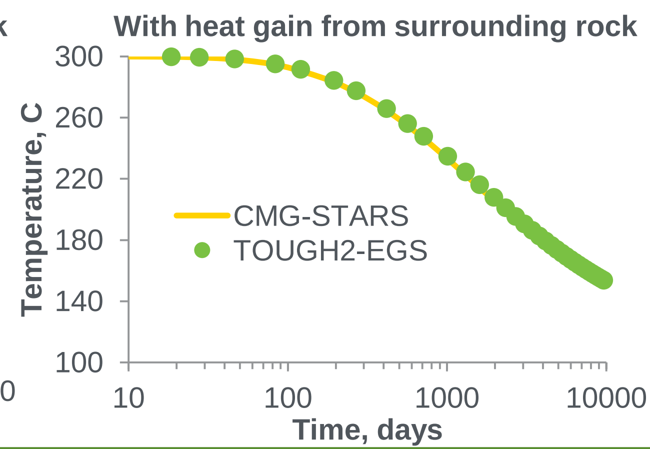




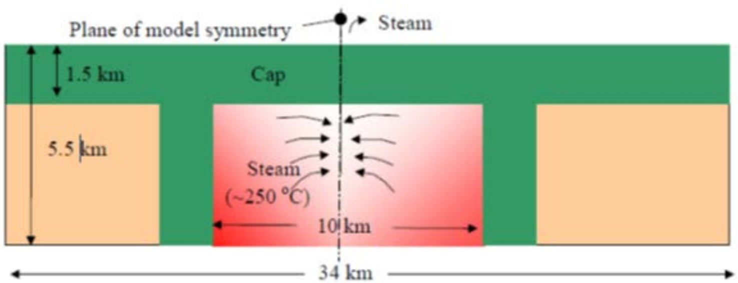


Heat Sweep in a Vertical Fracture



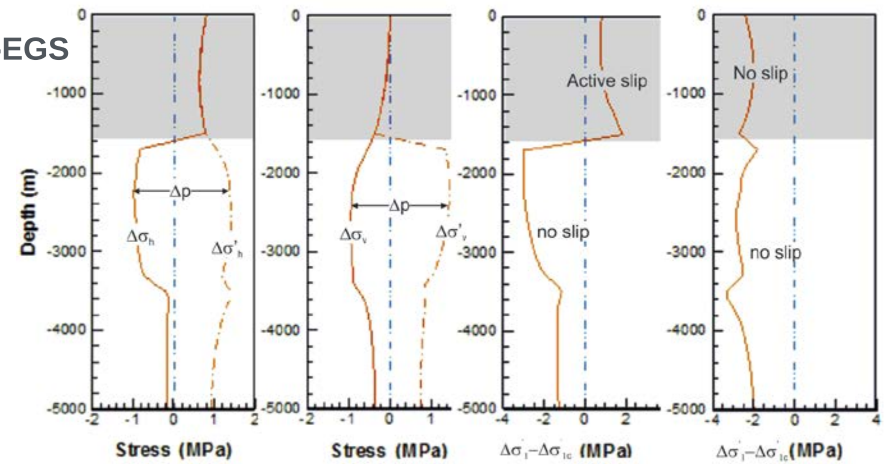


Verification: Against published simulation study (Induced-MEQ study the Geysers, Rutqvist et al.,2006)

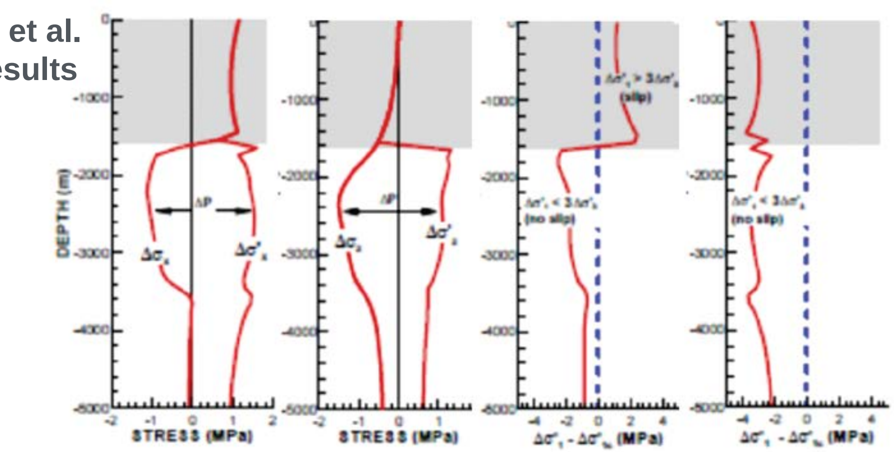


Schematic of model geometry for coupled THM modeling of steam production at the Geysers Geothermal Field

TOUGH2-EGS results

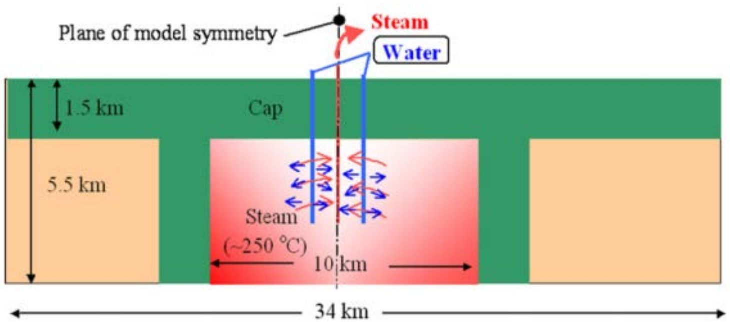


Rutqvist et al. (2006) results



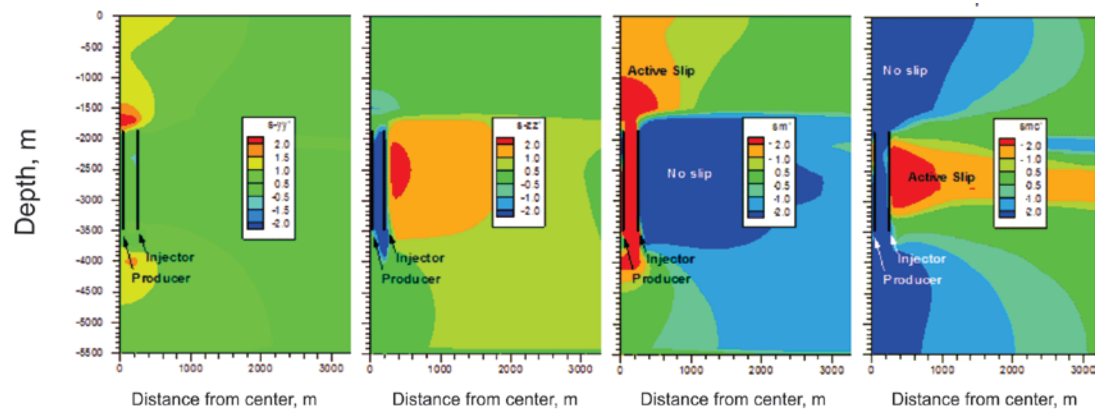
Ref: Rutqvist J., J. Birkholzer, F. Cappa, C.M. Odenburg, and C.F. Tsang, Shear-Slip Analysis in Multiphase Fluid Flow Reservoir Engineering Applications using TOUGH-FLAC, TOUGH Symposium, LBNL, Berkeley, California, 2006.

Verification: Against published simulation study (Induced-MEQ study the Geysers, Rutqvist et al.,2008)

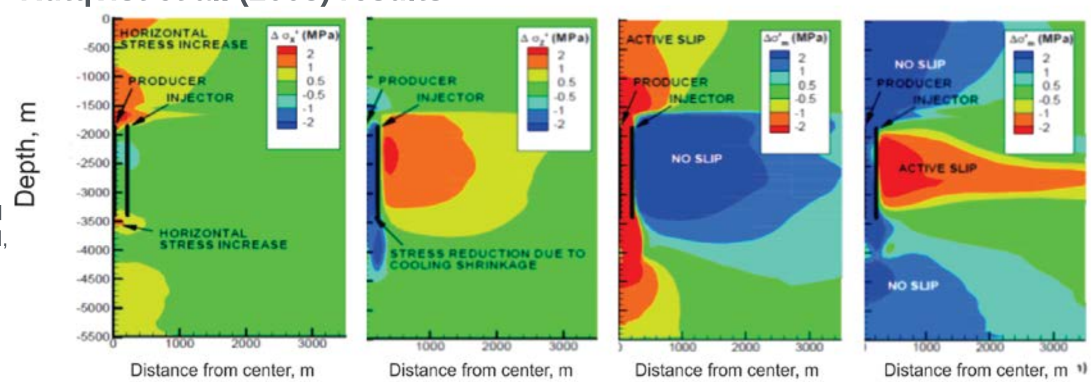


Schematic of model geometry for coupled THM modeling of steam production and water injection at the Geysers Geothermal Field

TOUGH2-EGS results



Rutqvist et al. (2008) results

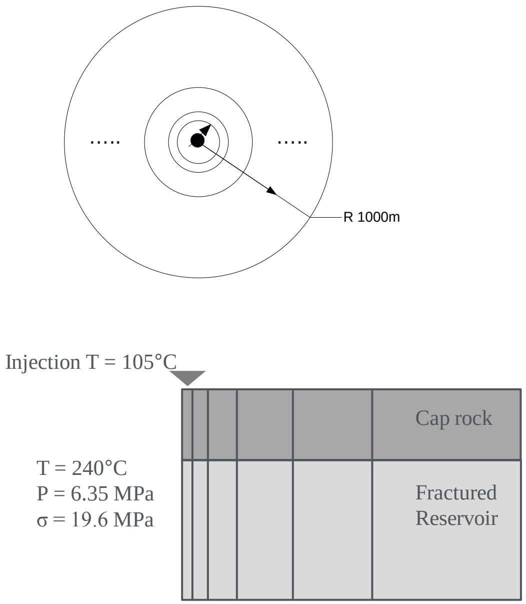


References

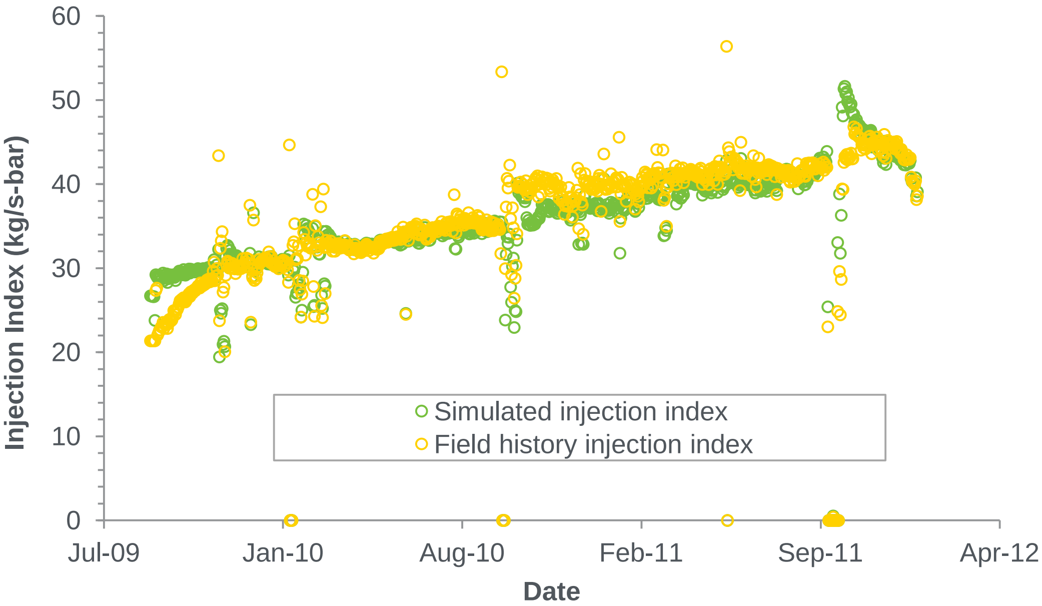
Rutqvist J., and Odenburg, C.M., (2007), “Technical Report#1: Development of fluid injection strategies for optimizing steam production at The Geysers geothermal field, California,” LBNL, Berkeley, California, LBNL-62577.

Rutqvist, J., and Odenburg, C.M., (2008), “Analysis of injection-induced micro-earthquakes in a geothermal steam reservoir, The Geysers geothermal field, California,” *in proceeding of The 42nd U.S. Rock Mechanics Symposium (USRMS)*, San Francisco, California.

Verification: Against field data

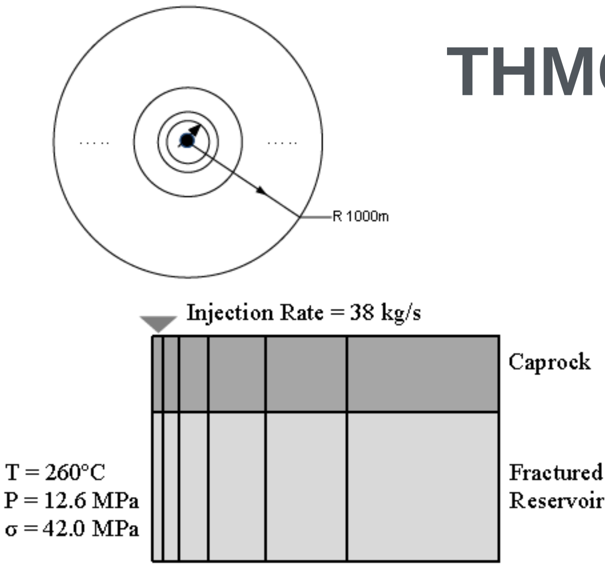


Model setup

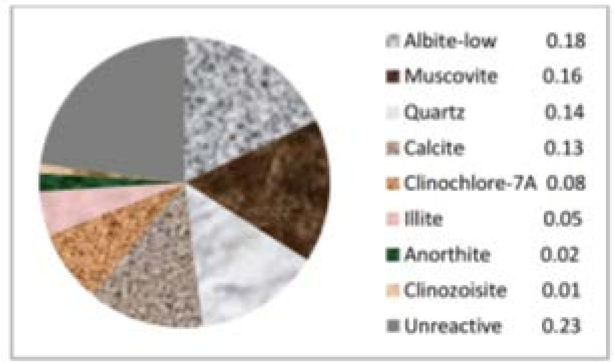


The injection index comparison between field data and simulation results: The well injection index increased with time indicates well stimulation due to cold water injection which can be captured by the simulation.

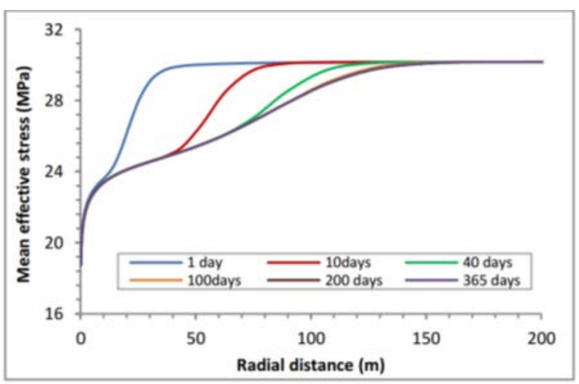
THMC application example



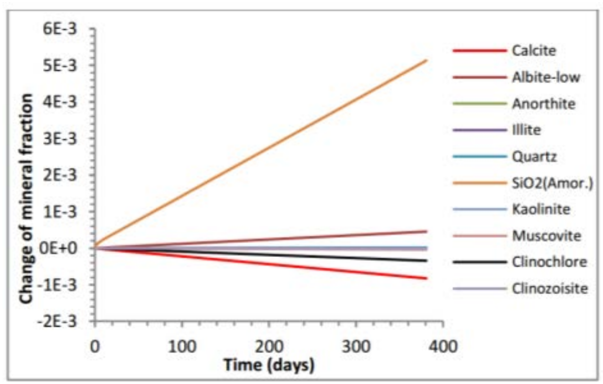
Model set up



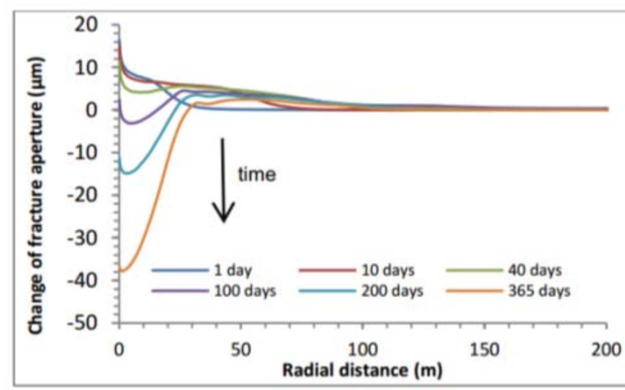
Initial mineral volume fraction



Results: Mean stress profiles



Results: Mineral volume fraction changes at the vicinity to the injector



Results: Fracture aperture change due to stress and chemical reaction effects

Future Directions

Complete the following list:

Milestone	Expected Completion Date
User's manual	Q1 2013
Speed up test for large problems (>1,000,000 grids)	Q2 2013
Public training	Q2, 2013
Final report	Q3 2013

Summary Slide

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- We have successfully developed a fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator and validated the simulator against analytical solution, a commercial reservoir simulator, published simulation study, and field data.
- The reservoir simulator developed from this project is among the first rigorous fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator.
- The developed simulators can be used to characterize EGS systems and provide practical approaches to assess the following:
  - Long-term performance
  - Optimum design
  - Operation strategies, and
  - Commercial feasibility
- The overall project is largely on schedule and budgeted appropriately

Project Management

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
01/01/10	12/31/13	01/01/10	12/31/13

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$1,191,893	$441,600	$992,917	$991,917	$991,917	$199,976

- A collaborated study with a geothermal field operator is on going
- Public training for the developed simulator is planned during June 2-3, 2013

BACKUP

List of Publications

- Yi, X., L. Hu, and Y. S. Wu, 2013, “Coupled Geomechanical And Reactive Geochemical Simulations For Fluid And Heat Flow In Enhanced Geothermal Reservoirs” in proceeding of The Thirty-eighth Workshop on Geothermal Reservoir Engineering, Stanford, California, 11-13 Feb.
- Fakcharoenphol, P., H. Kazemi, S. Charoenwongsa, and Y.S. Wu, 2012, ”The Effect of Water Induced Stress to Enhance Hydrocarbon Recovery in Shale Reservoirs”, SPE 158053, presented at the 2012 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, 8-10 Oct.
- Hu, L., P. H. Winterfeld, P. Fakcharoenphol, Y.S. Wu, K. Zhang, T. Xu, 2012, “A novel fully coupled flow and geomechanics model in fractured and porous geothermal reservoirs,” TOUGH symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California, 17-19 Sep.
- Fakcharoenphol, P., L. Hu, Y.S. Wu, S. Charoenwongsa, and H. Kazemi, 2012, “A Fully Coupled Flow and Geomechanics Model: Application to Enhanced Geothermal Reservoirs,” in proceeding of the TOUGH symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California, 17-19 Sep.
- Fakcharoenphol P., L. Hu, and Y.S. Wu, 2012, “Fully-Implicit Flow and Geomechanics Model: Application for Enhanced Geothermal Reservoir Simulations” in proceeding of The Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, California, 30 Jan- 1Feb.
- Fakcharoenphol, P. and Y. S. Wu, 2011, “A Fully-Coupled Flow-Geomechanics Model for Fluid and Heat Flow in Geothermal Reservoirs”, in proceeding of the 2011 GRC Annual meeting, San Diego, CA, 23–26 Oct.
- Fakcharoenphol, P. and Y. S. Wu, 2011, “A Coupled Flow-Geomechanics Model for Fluid and Heat Flow for Enhanced Geothermal Reservoirs”, ARMA 11-213, in proceeding of the 45th US Rock Mechanics / Geomechanics Symposium, San Francisco, CA, 26–29 Jun.
- Fakcharoenphol P., A. Jamili, and Y.S. Wu, 2010, “Numerical Simulation of Coupled Processes for Multiphase Flow, Rock Deformation, and Heat Transfer in Enhanced Geothermal Systems,” presented at the 2010 GSA Denver Annual Meeting, Denver, Colorado, 31 Oct –3 Nov.