LLNL-TR-838525

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL 5-2428: Fracture Permeability and Seismic Slip Behavior

K. A. Kroll, M. M. Smith, Y. Hao, G. Davila, F. Fei, L. Frash, J. Burghardt, C. Marone, K. B. Richards-Dinger

August 5, 2022

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL 5-2428: Fracture Permeability and Seismic Slip Behavior

1. **Coupled Investigation of Fracture Permeability Impact on Reservoir Stress and Seismic Slip Behavior**
   - Organization or Affiliation: Lawrence Livermore National Laboratory; 7000 East Ave Livermore Ca 94551
   - Principal Investigator: Dr. Kayla A. Kroll, Seismology Deputy Group Leader
   - Contact information: kroll5@llnl.gov
   - Subcontractors and/or Participating Organizations:
     - Los Alamos National Laboratory, Los Alamos, NM
     - Pacific Northwest National Laboratory, Pasco, WA
     - Pennsylvania State University, State College, PA
     - Consultant (Keith Richards-Dinger), Redlands, Ca
   - Project Start and End Date: Feb/2022 – Feb/2024

2. **Project Objectives and Purpose**
   - *Provide a full suite of THMC properties and states, including a probability density function (PDF) of each with associated uncertainty under geothermal conditions, to improve predictive models.*
   - *Develop an improved understanding of the physical processes and conditions that influence EGS operations to aid as a resource for optimization.*
   - *Optimize spatiotemporal predictions for pressure and stress states and the associatedseismic hazard for a variety of operational scenarios.*
   - Our goal is to develop, apply and validate a holistic thermal, hydrologic, mechanical, and chemical (THMC) workflow that also includes evaluation of induced seismic slip in EGS reservoirs. We will integrate experimental and modelling approaches to reduce parameteruncertainty and better predict and mitigate seismic hazard at Utah FORGE and future EGS sites.We propose a novel approach that incorporates 3D physics-based Earthquake simulations in THMC models, herein referred to as "THMC+*E*" models. This capability will enable improvedengineering decisions at Utah FORGE and move EGS operations toward repeatable, robust, economically viable, and socially accepted development. Utah FORGE management and future EGS operators may employ results of THMC+E models for decision making purposes throughout the lifetime of the field operation. For example, before production well installation, our THMC+*E* models will predict circulation scenarios and related seismic hazard for a suite ofpossible well locations and flow rates, thus enabling evaluation of optimal production well placement. Such efforts will be conducted throughout the lifetime of the project, whereby additional laboratory experiments will constrain key model parameters and machine learning (ML) will reduce the size of the parameter space and the associated uncertainty. THMC+*E* simulations will enable exploration various circumstances that may hinder EGS success and develop mitigation strategies.

3. **Technical Barriers and Targets**
   - Technical challenges:
     - The rock coring and fracturing apparatus at LLNL that is being used to prepare the plugs for the permeability and rock strength experiments (Tasks 2.2 and 2.1, respectively) had to be relocated and installed before use by this project. This equipment is quite large and required additional specialty equipment to transport. This process has been completed and core plugs are currently being prepped. the first round of sub-cores have been prepared from one of the six drill cores received (10961-ft depth). These sub-cores include a suite of 1.5"-diameter sub-cores centered on foliated granodiorite features to be split between LLNL and LANL, as well as (4) 1"-diameter

samples provided to LANL as contingency samples in the event that their new platens do not arrive in time for experimental deadlines.

- One goal of this project is to conduct permeability (at LLNL) and rock strength (at LANL) experiments on the same samples. This requires the experimental setups and design at the two institutions to be the same. In order to facilitate this, a 1.5" triaxial direct-shear platen set has been ordered (due for delivery by mid-August 2022). These platens will make the LANL test samples compatible with LLNL facilities to simplify cross-lab core-sharing activities.

- Technical accomplishments:
  - The first set frictional experiments were performed on gneissic powders. Frictional results were modeled to produce best-fitting estimates of rate-state parameters.
  - Coupled THMC modeling: We have added a thermal solver to our exascale poromechanical reservoir simulation code, GEOSX, which will allow for the computation of coupled THMC processes along fractures in the reservoir.

4. Technical Approach

- Technical approach:
  - o EGS energy production depends on sustained permeability and sufficient fluid flow through pre-existing or induced fractures in deep hot rock. Currently, there are no comprehensive and fully validated workflows that address coupled processes (e.g., geochemical alteration alongengineered fractured pathways, slip-induced permeability changes, thermo-poro-elastic effects and induced seismicity) in EGS environments. To address this need, we will integrate high- temperature geomechanical and frictional experiments [Task 2.1;] and geochemical experimental data (Task 2.2) with exascale computations of reactive transport, geomechanics (Task 3) and associated seismic/aseismic displacement (Task 4; see Figure 1, Workplan Section,and SOPO for complete description of each task). This will result in an experimentally constrained, reservoir-scale reactive transport and earthquake/slip simulation (THMC+*E*) models for the Utah FORGE site and can inform decision making for reservoir planning purposesprior to drilling of new wells (production or injection), for evaluation of field operational optionsthroughout the lifetime of the project, and for improved understanding of the relationship between fluid circulation and seismic processes that may hinder sustainability. ***This proposed work uses an experienced project team and new available capabilities in both experimentation and high-performance computer modeling to advance the state of EGS at Utah FORGE and for the broader EGS community.***
- Current key issues
  - o Coupled THMC modeling: We have added a thermal solver to our exascale poromechanical reservoir simulation code, GEOSX, which will allow for the computation of coupled THMC processes along fractures in the reservoir.
  - o Permeability evolution, rock strength and frictional properties: We are currently setting up a suite of high-temperature experiments that will allow us to measure the site-specific evolution of permeability as mineral precipitate or dissolve with fluid flow along natural and/or Brazilian fractures. We will measure the rock and fracture strength on the same sample and finally conduct double-direct shear experiments that will allow us to measure the frictional properties that control the propensity for seismic or aseismic slip on the fractures in the reservoir.

5. Project Timeline (list milestones achieved and/or decision points)

- First milestones are set for completion by the end of this projects 3rd quarter (Utah FORGE quarter 5) as described in our milestone table.

Prepared by LLNL under Contract DE-AC52-07NA27344.

6. Technical Accomplishments

- Task 2.1.1: Double-direct shear experiments: The first set frictional experiments were performed on gneissic powders. Frictional results were modeled to produce best-fitting estimates of rate-state parameters.

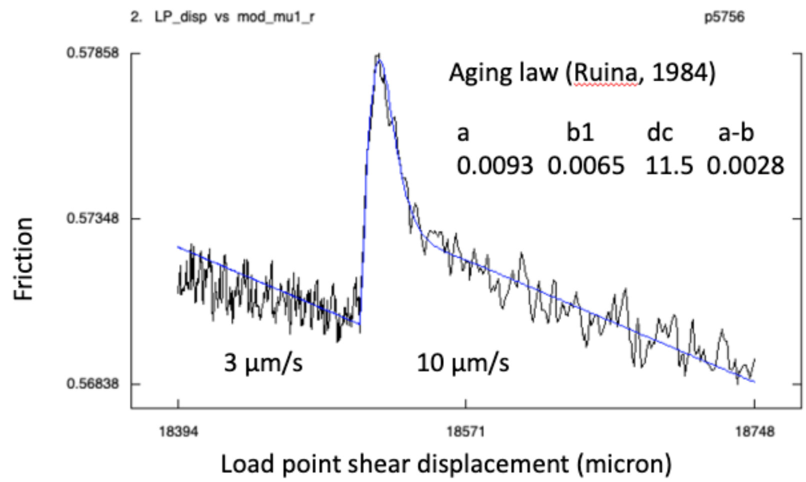

Figure 1: Rate-state modeling of velocity step test at 75 MPa normal stress for gneissic powder sample (< 125 mm p5756). Best fitting parameters listed in upper right.

These results will be used in Task 2.3 to derive a probability distribution of frictional parameters that will then be used in Task 4 in the THMC+E earthquake simulations such that the simulations are using site specific values and investigating the impact of the uncertainty on those parameter values.

- Task 3.1.1: Reactive Flow and Transport modeling: We have added a thermal solver to our exascale poromechanical reservoir simulation code, GEOSX, which will allow for the computation of coupled THMC processes along fractures in the reservoir.

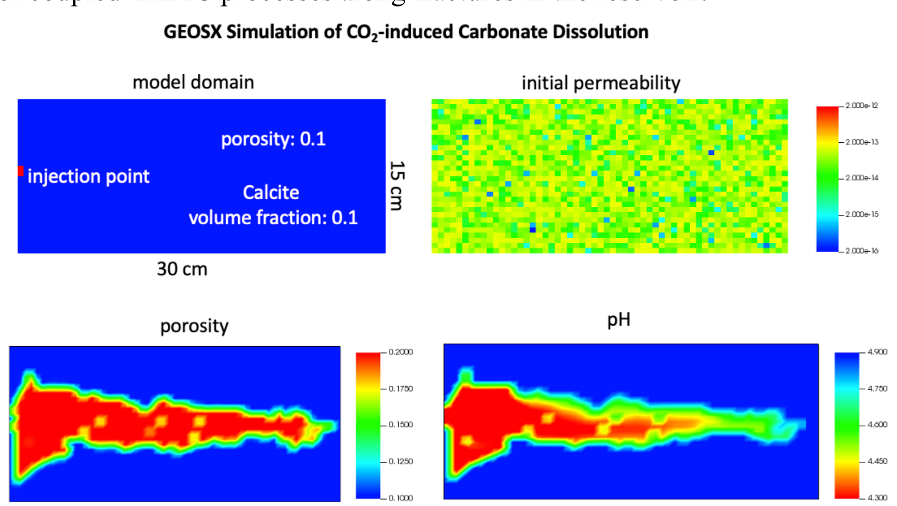

Figure 2: Benchmark study of the reactive flow and transport solver in GEOSX that shows the effects of CO2 dissolution of carbonate minerals.

- Task 3.1.2: Coupled THMC modeling: The thermal module will allow for completion of the Task 3 efforts to compute the time-varying pressure and stress distribution due to fluid circulation. These results will be passed to Task 4 for THMC+E modeling.

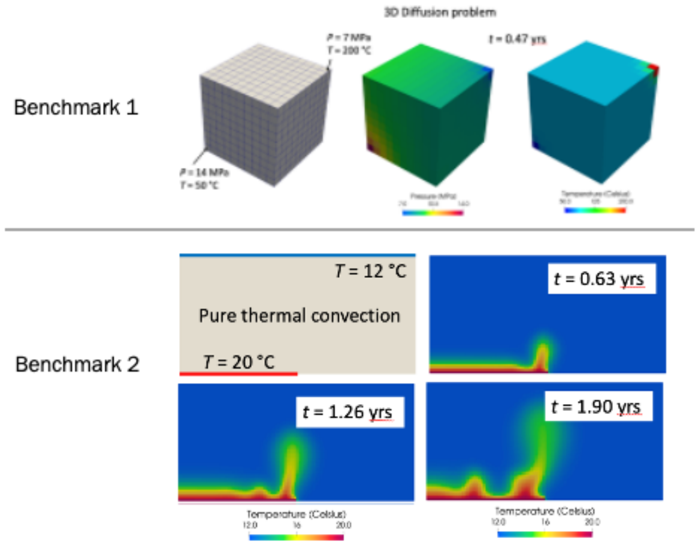

Figure 3: Benchmark studies for the validation of the thermal solver in GEOSX. Benchmark 1 shows the pressure and temperature driven flow for 3D diffusion, and Benchmark 2 shows classic "fingering" that develops near the high temperature boundary in pure thermal convection, which is qualitatively similar to results from the TOUGH2 code.

7. Challenges to Date

- Variance:
  - Experimental work carried out under this project at LLNL and through subcontract to LANL requires a level of effort and supplies not commiserate with the quarterly funding allotment provided by the Sponsor. This is owning to the fact that the experimental apparatuses require long periods of dedicated run time. The experimental results and the apparatus may be subject to failure by starting and stopping the experiments. Therefore, the LANL and LLNL are currently waiting until the second quarter of funding to arrive before starting the experiments and then they will perform the experiments in a solid block. This will cause funding to be spent in bursts rather that uniformly over the project year. The project milestones are set to address this issue.
  - Note, this project officially started on February 4, 2022. First quarter funding (for Feb/March/April 2022) arrived on March 7, 2022. Funding for quarter 2 (May, June, July 2022) has not yet been provided to LLNL for this project despite being requested on May 11, 2022. When the project PI inquired about this (Aug 2, 2022), we were informed that we should provide monthly invoices for expenditures and that a request had been made on behalf of Utah FORGE on June 21, 2022 requesting invoices for April and May. LLNL submitted a quarterly report with the invoices for the Feb, March, April 2022 quarter on April 30, 2022. The May invoice was not submitted because the funding for the May/June/July quarter has not yet arrived therefore no money could be spent. LLNL endeavors to send monthly invoices even if they report zero sending.

8. Conclusion and Plans for the Future

- Project started late due to contracting issues, issues transferring funds to the lead intuition, and subcontracting, therefore, the project timeline is not in-line with the Utah FORGE timeline (e.g. this project is delayed by nearly 2 quarters from the Utah FORGE project). In light of those circumstances, the project has just really gotten started. We have held a kickoff meeting, received our core samples from Utah FORGE and have begun generating plugs for the permeability and rock strength experiments. We have also nearly completed the addition of a thermal module to the multi-physics poromechanical code which will be used for Task 3 efforts. Currently, we are set to meet our milestones as outlined in the milestone table.

9. Geothermal Data Repository

- None

10. Publications and Presentations, Intellectual Property (IP), Licenses, etc.

- None

Prepared by LLNL under Contract DE-AC52-07NA27344.