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EGS Collab Project (Task 12): High Temperature Laboratory Experimentation to Support EGS Stimulations

Project Officer: Lauren Boyd

Total Project Funding: $9M, PY2 – $10.7M

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Track 2: EGS Collab

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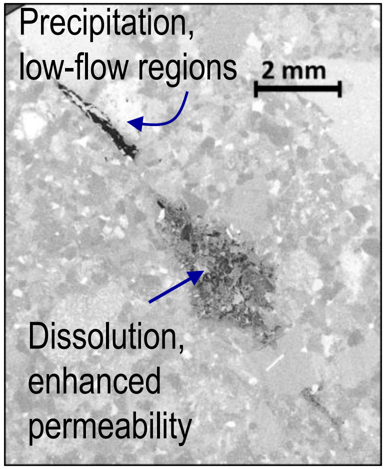
Relevance to Industry Needs and GTO Objectives

GTO Need: Predicting the impact of high-temperature fluid-rock reactions on **fluid permeability** in fractured enhanced geothermal systems is critical for **sustained operation**.

The objectives of these high-temperature experiments are:

- To investigate the role of chemistry and stress on fractured rock permeability at geothermally relevant temperatures.
- To produce experimental datasets to calibrate reactive transport and mechanical models for better long-term EGS permeability prediction.



X-ray CT image of reacted geothermal core, 200C. Smith et al., 2013

Project Integration: Task 12 and lab-based measurements are designed based on Modeling & Monitoring team input; results will be made available to inform future experiments.

GTO Goal: Reducing costs & risk

Results from these experiments and associated laboratory measurements will:

- Help constrain the impact of fluid-rock reaction on fracture flow at depth
- Validate and assess errors associated with the use of newly determined kinetic rate laws for relevant geothermal mineral phases
- Provide geochemical & geomechanical parameters for better interpretation of borehole monitoring data and simulations

The outcome of these experiments will:

- Allow better assessment of risk to sustained fluid permeability posed by potential chemical reaction at high temperatures
- Assist in better and more economical operation of enhanced geothermal systems

Methods/Approach – Task 12 overview

- Obtain and fracture subcores
- Nondestructively characterize cores with X-ray computed tomography (XRCT)
- Conduct four reactive transport experiments at geothermal conditions to evaluate fracture permeability
- Produce experimental datasets useful for model validation
- Form reactive transport model to simulate extent of reaction and flow response
- Determine displacement(s) resulting from chemical reaction

Preparation of fractured core samples

- Obtained Poorman phyllite cores with ideal sulfide content and level of foliation.
- Produced 4(+) fractured samples for use in experiments.
  - Method 1: subcoring around existing core fractures, suffered from chipping/flaking
  - Method 2: inducing fractures in subcores pre-drilled in alignment with foliation

XRCT characterization of samples

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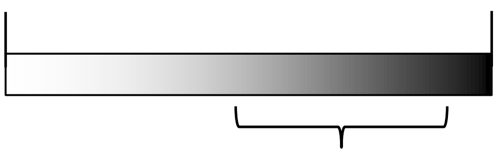
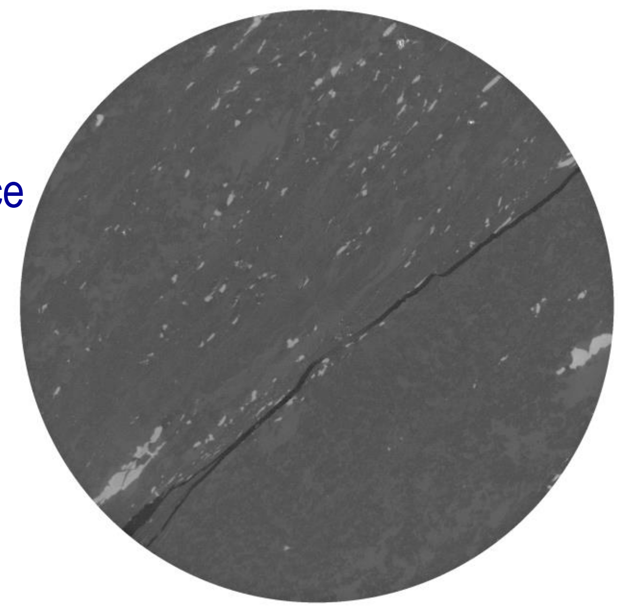
- Five samples have been nondestructively 3-D imaged with X-ray computed tomography (XRCT) prior to reaction.
- Gray-scale XRCT value can be correlated to mineralogy (determined by conventional X-ray diffraction, microprobe analyses).
- Comparison of pre- and post-reaction images will provide quantitative measures of changes to mineral reaction, aperture volume, and deformation.

X-ray bright sulfides

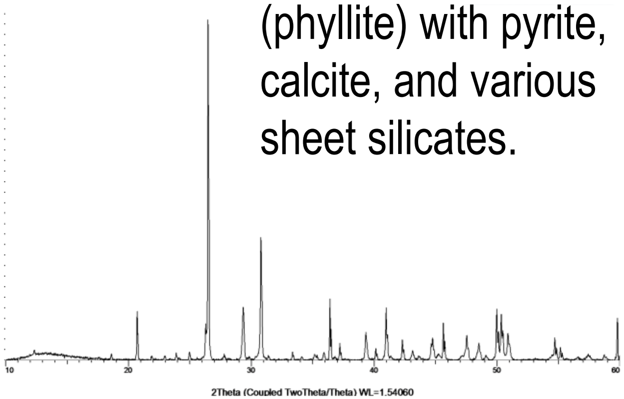
fracture void space



constituent minerals (e.g., biotite, muscovite)



X-ray diffractogram (phyllite) with pyrite, calcite, and various sheet silicates.



Gray-scale XRCT cross-sectional “slice” and segmented regions

High-temperature experiments to support EGS permeability

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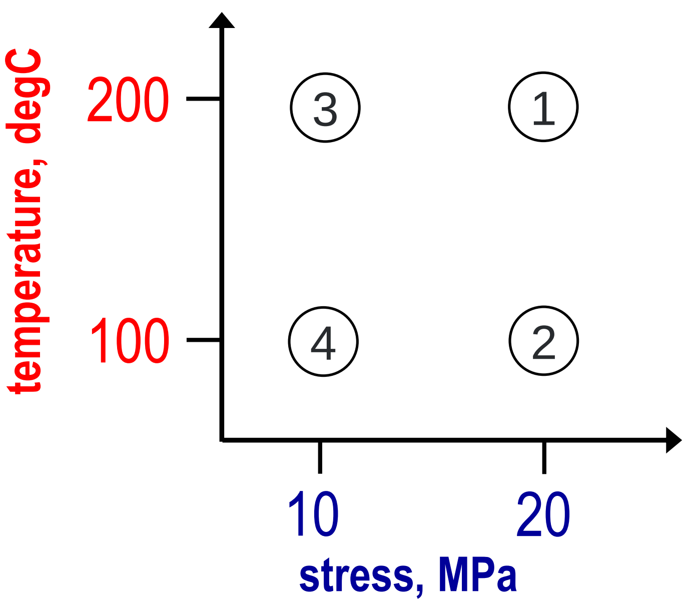
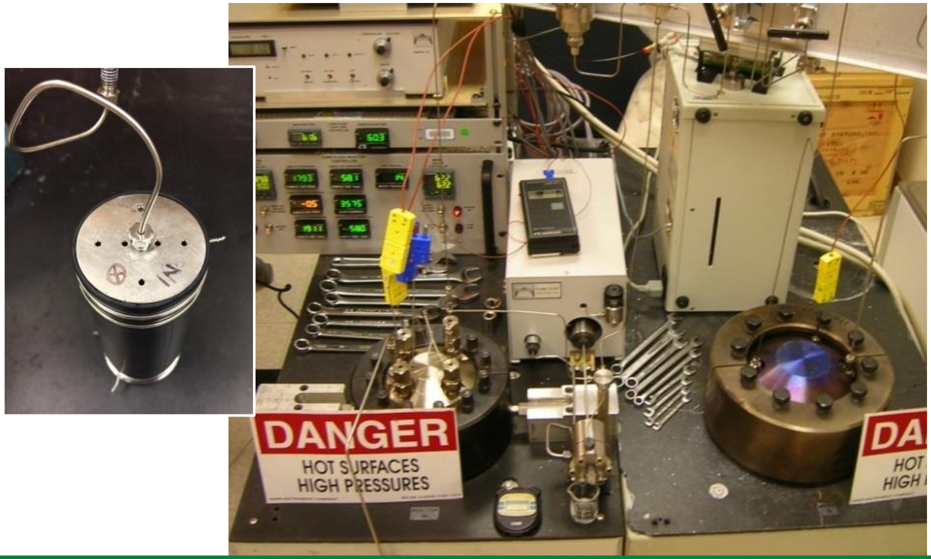
- Cores will be reacted at two temperatures and fixed stress, as well as under two varying stresses and fixed temperature, to evaluate the impact of chemical reaction and stress on fracture permeability.
- Experimental conditions will be tied closely to EGS site conditions.
- Pressure, flowrate, solution chemistry will be monitored through time.

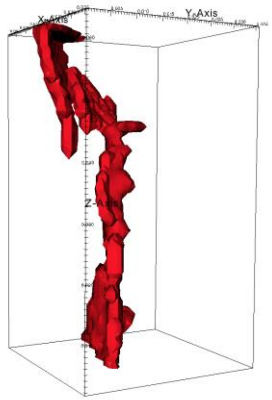


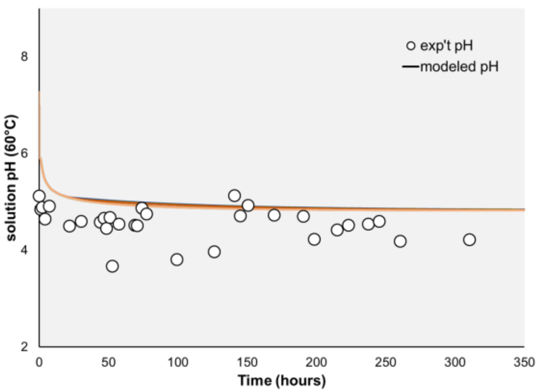


Reactive transport model

- Experimental solution chemistry and hydrologic flow data simulated with reactive transport model (using newly derived kinetic rate laws for relevant mineral phases*).
- Comparison with predictions to validate the use of these new rate laws, as well as bound the *fraction of accessible reactive mineral* along fracture walls (currently a poorly constrained quantity)

Incorporation of XRCT-observed fractures (green) into continuum reactive transport model for prediction of void space increase (red) and solution chemistry effects from fluid-rock interaction (Smith & Hao et al., 2017)





*Smith, M.M., and S.A. Carroll (in review) Biotite dissolution kinetics at temperatures above 100C. *Chem. Geol*.

Smith, M.M., Y. Hao, and S.A. Carroll, 2017. Development and calibration of a reactive transport model for carbonate reservoir porosity and permeability changes based on CO_2 core-flood experiments. *Int. J. Greenhouse Gas Contr.* **57**, 73-88.

Smith, M.M., Z. Dai, and S.A. Carroll, 2017.Illite dissolution kinetics from 100 to 280C and pH 3 to 9. *Geochim. et Cosmochim. Acta*, **209**, 9-23.

Lammers, K.L., M.M. Smith, and S.A. Carroll, 2017. Muscovite dissolution kinetics as a function of pH at elevated temperature, *Chem. Geol.*, **466**, 149-158.

Smith, M.M., and S.A. Carroll, 2016. Chlorite dissolution kinetics at pH 3-10 and temperature to 275C. *Chem. Geol.* **421**, 55-64.

Analysis of deformation resulting from chemical reaction

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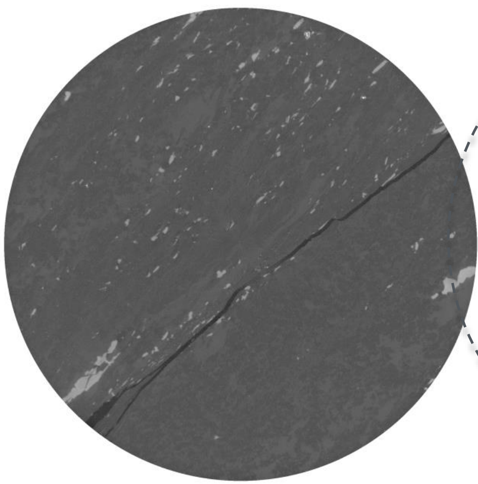
- Particle image velocimetry uses “tracer particles” (X-ray bright sulfide minerals) within a core to estimate mechanical deformation.

EGS Collab core
XRCT gray-scale



segmented fracture, pyrite grains

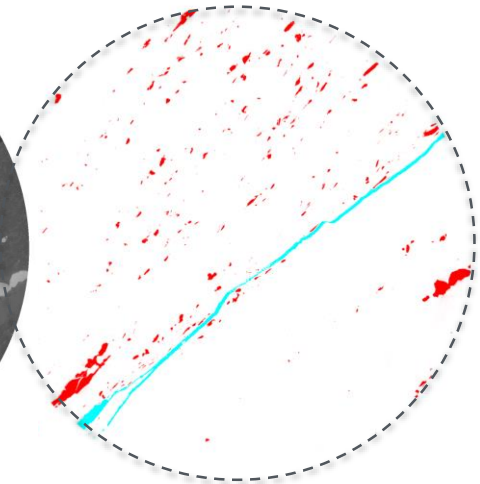


Figure 3, Walsh et al., 2016

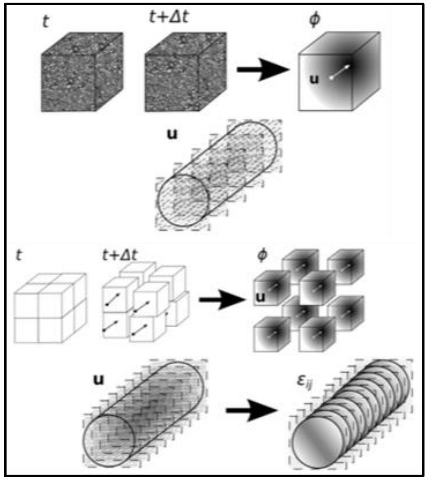
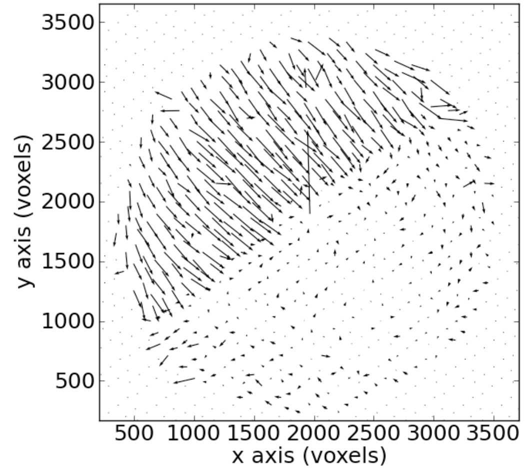
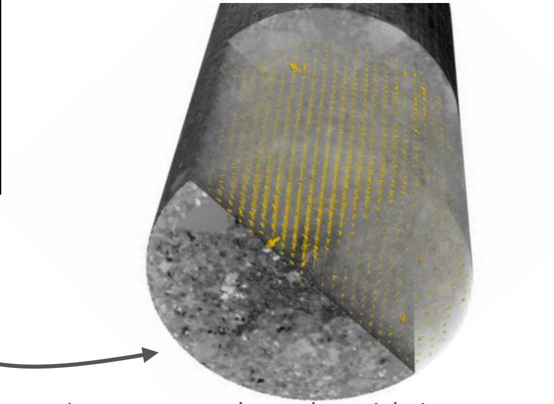


Figure 6, Walsh et al., 2013.





Walsh, S.D.C., M.M. Smith, and S. Carroll, 2013. Decoupling reaction and deformation in natural fractures with X-ray micro-tomography and particle image velocimetry. *Amer. Rock Mech. Assoc.*, **13**-445.

Walsh, S.D.C., M.M. Smith, S. Carroll, D. Crandall, 2016. Non-invasive measurement of proppant pack deformation. *Int J Rock Mech Mining Sci*, **87**: 39-47.

Geomechanical characterization to support EGS simulations

- In response to EGS Collab Modeling & Simulation survey results (J. Burghardt & M. White), additional rock characterization/ measurement needs have been assigned:
  - *Essential measurements*: isotropic quasi-static elastic properties (H. Sone, S. Bauer, S. Nakagawa), isotropic thermal conductivity (S. Bauer, T. Kneafsey) and thermal expansion coefficient (C. Strickland)
  - *Other identified priorities*: transversely isotropic quasi-static elastic properties, isotropic fracture toughness, porosity, low-frequency elastic moduli, rock bulk density, thin section description
  - These are not trivial measurements and a few good estimates at relevant conditions are more valuable than many at atmospheric conditions.

- Following detailed core logging, samples should available to all EGS Collab members.

Technical Accomplishments and Progress

Experimental samples obtained, fractured, and imaged.

Pressure transducers were re-calibrated; experimental flow lines overhauled.

Experiments 1 & 2 scheduled through November 2017-March 2018.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Experimental cores prepared and characterized	Satisfactory samples produced; pre-reaction imaging completed	8/15/17
Complete laboratory-scale experiments at variable temperature, constant stress	Experiments to begin in November.	Ongoing (3/30/18)

Research Collaboration and Technology Transfer – Task 12

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- Poorman Formation rock core samples shared within EGS Collab for geomechanical testing (S. Bauer).

- Discussions within Laboratory Experiments & Measurements working group have identified core sampling needs from the current Experiment #1 boreholes

- Most current results to be presented at Stanford Geothermal Workshop (February 2018).

Future Directions (FY18, FY19)

- Laboratory-scale experiments will begin November 2017. Each experiment requires ~1 month of lab time (based on previous experiment at similar mineralogy and temperature) as well as 1+ month chemical analysis time.
- We expect no delays in post-reaction XRCT imaging due to regularly scheduled beam time allotments.
- Reactive transport modeling will begin after completion of first two experiments.
- Geophysical and geomechanical measurements to begin early FY2018; results will be shared via EGS Collab data repository.

Milestone or Go/No-Go	Status & Expected Completion Date
Complete laboratory-scale experiments at variable temperature, constant stress	Ongoing; 3/30/18
Complete laboratory-scale experiments at corresponding temperature, variable stress	3/30/19

Summary – Impact of high-T reaction

- The results of these experiments provide a better assessment of high-temperature chemical reaction effects on sustained fluid permeability
- Fractured core samples fabricated and imaged in preparation for four high-temperature experiments at representative geothermal temperature (100-200C) and stress conditions (≤20 MPa).
- Core sampling requirements coordinated across EGS Collab partners in order to measure needed geomechanical parameters identified by Modeling & Simulation Group (samples to ship out after borehole logging completed).