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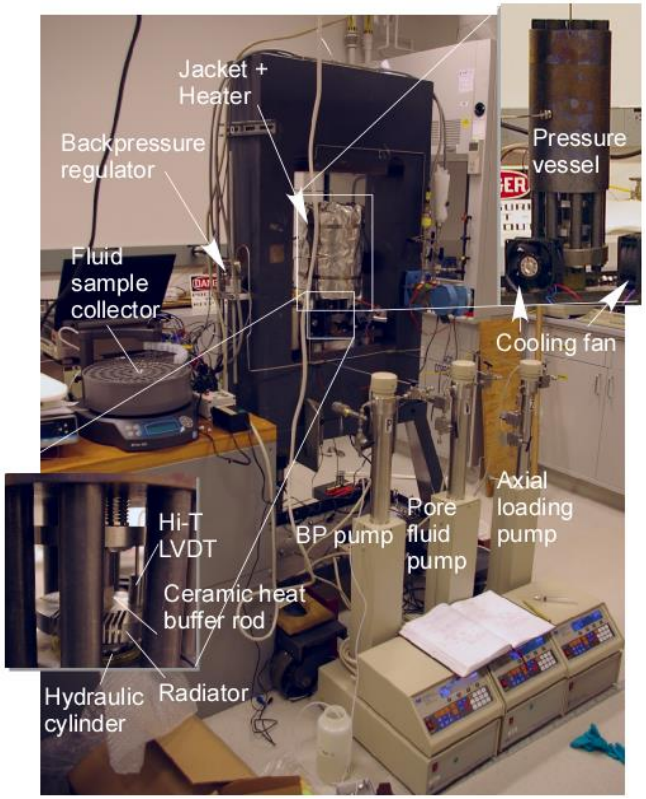
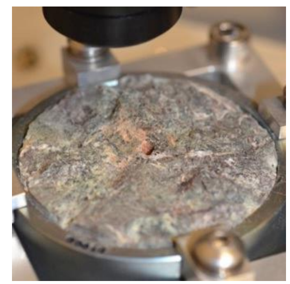
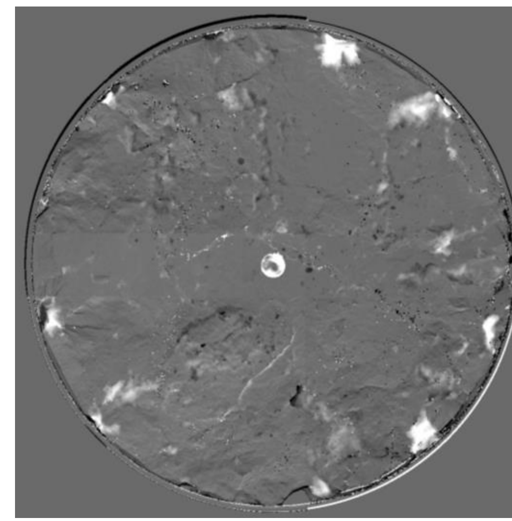






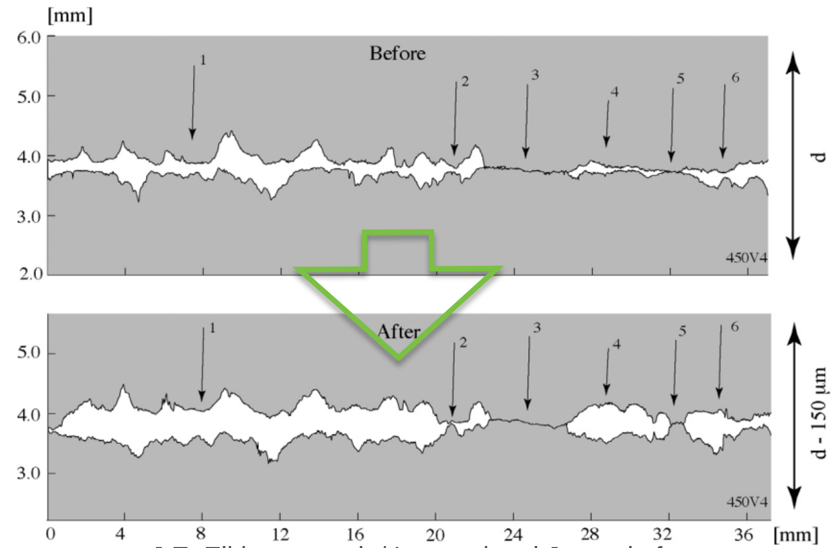
Sustainability of Shear-Induced Permeability for EGS Reservoirs – A Laboratory Study

Project Officer: Lauren Boyd
FY15 Project Funding: $350K
May 2015

Tim Kneafsey
Lawrence Berkeley National Laboratory
Reservoir Fracture Characterization & Fluid Imaging

Relevance/Impact of Research

- Sustainable production from geothermal reservoirs depends on development and maintenance of suitable fracture permeability.
- Fracture apertures will change over time due to dissolution and precipitation, mechanical deformation of asperity contacts and propping mineral grains (functions of T, σ, mineralogy, chemistry, local flow, topology, grain size).



J.E. Elkhoury et al. / International Journal of Greenhouse Gas Control 16S (2013) S203–S215

The primary objective of this research is to understand how different rock types, mineral and fluid compositions, and fracture surface textures determine the longevity of fracture apertures, so that selection of reservoir rock can be economically optimized to reduce future refracturing. We are performing laboratory tests to study this in a custom apparatus at conditions relevant to EGS, with temperatures up to 250ºC (design maximum 300ºC).

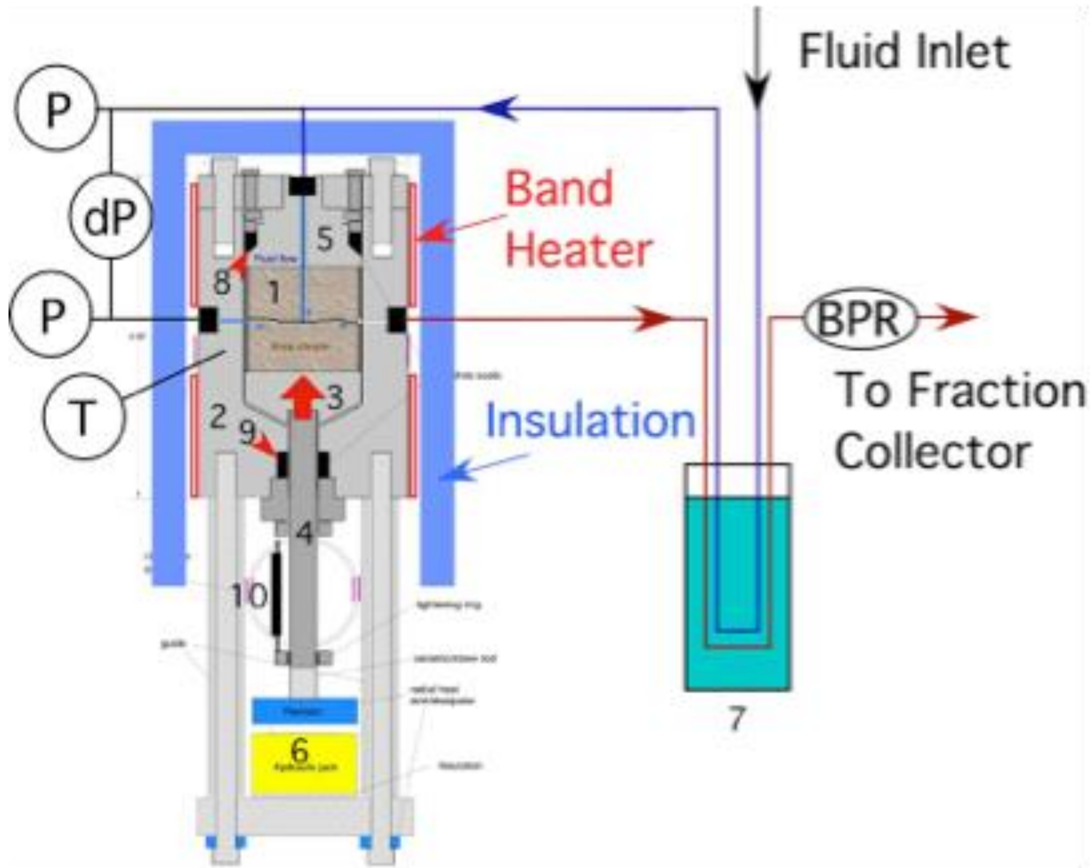
Our approach is to perform a number of long term (up to several months) laboratory experiments using relevant rock samples with different mineralogies to explore fracture sustainability under EGS conditions. We use an apparatus that allows direct application of a normal force on the fracture faces of a single fracture in a sample having a sheared, tensile fracture. We flow brine of a specified composition through the aperture, and simultaneously measure the fracture permeability and closure. We collect the effluent water for chemical and isotopic analysis. We are numerically modeling our tests and comparing experimental and numerical results.

Process

- Design experimental test strategy
- Design and fabricate test cell to implement strategy
- Identify and obtain **relevant** rock samples (reservoir rock cores)
- Prepare (machine) rock samples and introduce fracture for test
- Characterize fracture profiles and rock mineralogy
- Perform long term tests and monitor/control:
  - temperature, pressure, and flow rate
  - pressure differential (indicates hydraulic aperture)
  - deformation
  - effluent chemistry and isotopic composition
- Characterize changes in profiles and mineralogy of samples
- Analyze data and simulate

Custom inert vessel and system allowing:

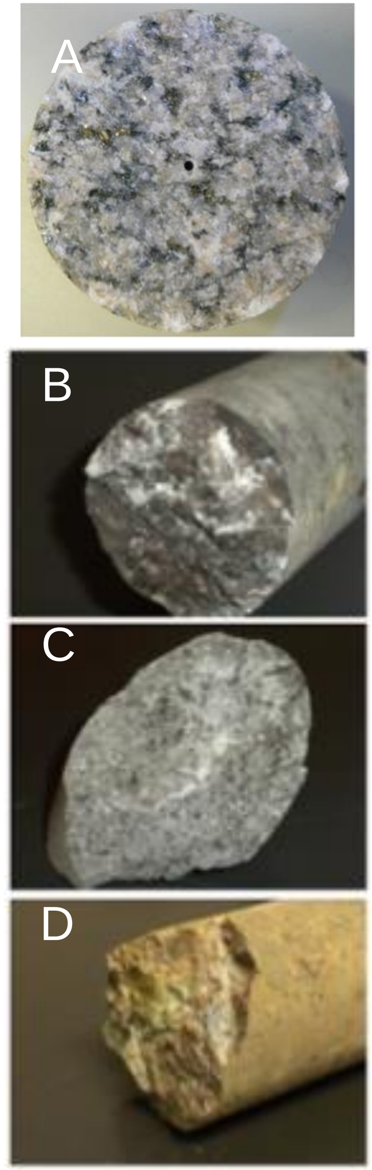
- geometrically applied shear offset (no stress)
- constant direct normal stress on fracture
- precision controlled flow of geothermal fluid
- temperatures up to 300ºC (elastomer problems)
- measurement of relevant parameters
- long term operation

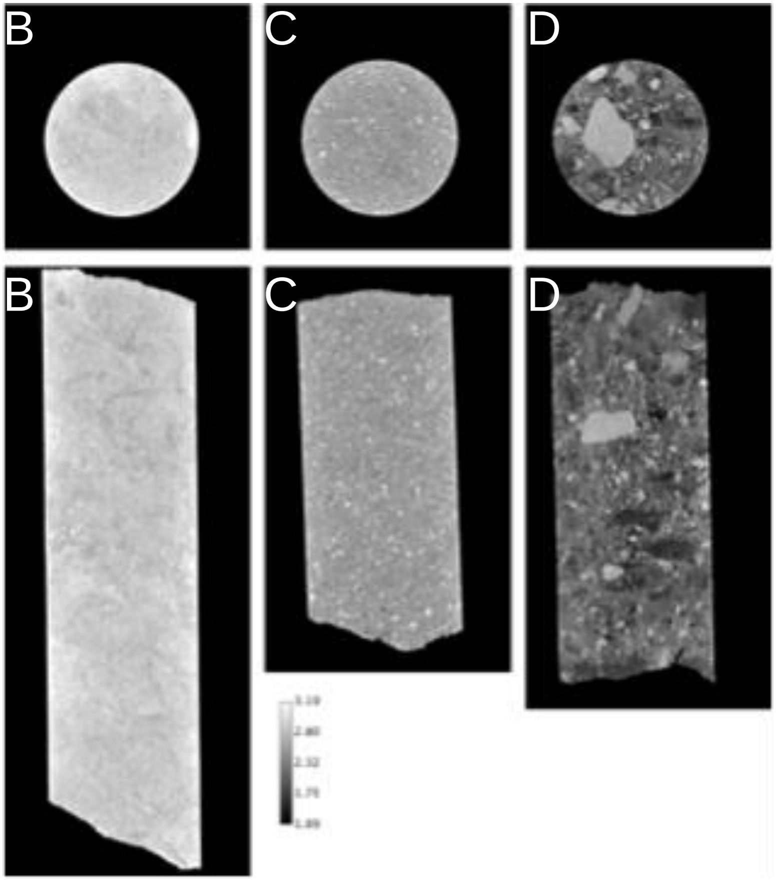


Samples

A. Stripa granite (150^{o}C, 20 MPa)
B. Meta-sedimentary rock* from 4873 ft, (250^{o}C, 20 MPa)
C. Meta-dacite* from 3945 ft (250^{o}C, 20 MPa)
D. Altered tuff* from 2310 ft (in progress)

* From Brady (Ormat)

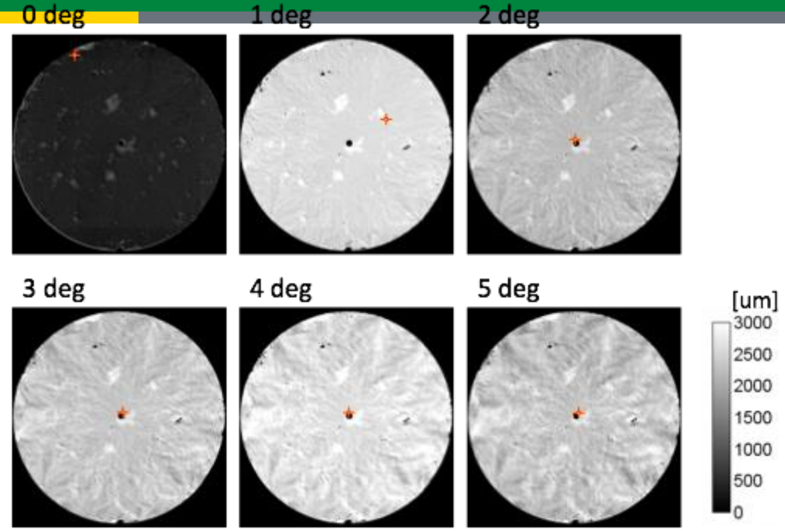




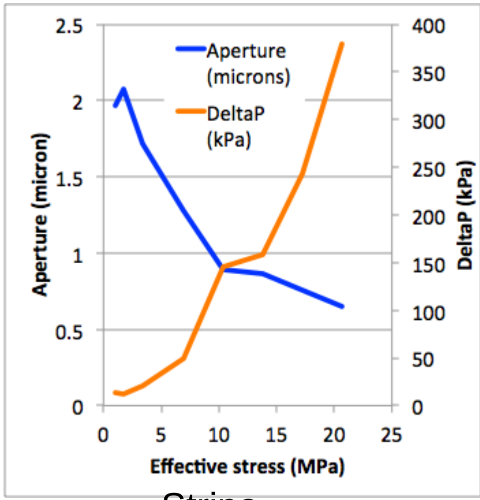
X-ray CT images of rock cores

Test Cycle (process)

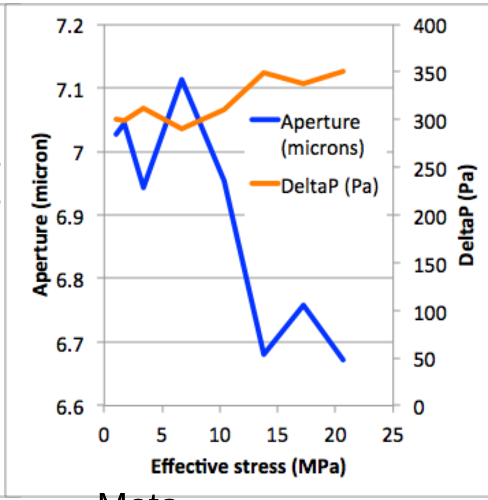
1. Specify angular mismatch of fracture faces (Ti pin used to hold rotation)
2. Assemble into apparatus
3. Apply normal stress
4. Flow fluid
5. Heat system
6. Continue flow, monitor pressure, differential pressure, temperature, collect fluid samples
7. Cool system
8. Stop flow
9. Remove sample
10. Model system geomechanics and geochemistry and compare to experiment (TOUGHREACT/ROCKMECH)



Aperture Change on Loading

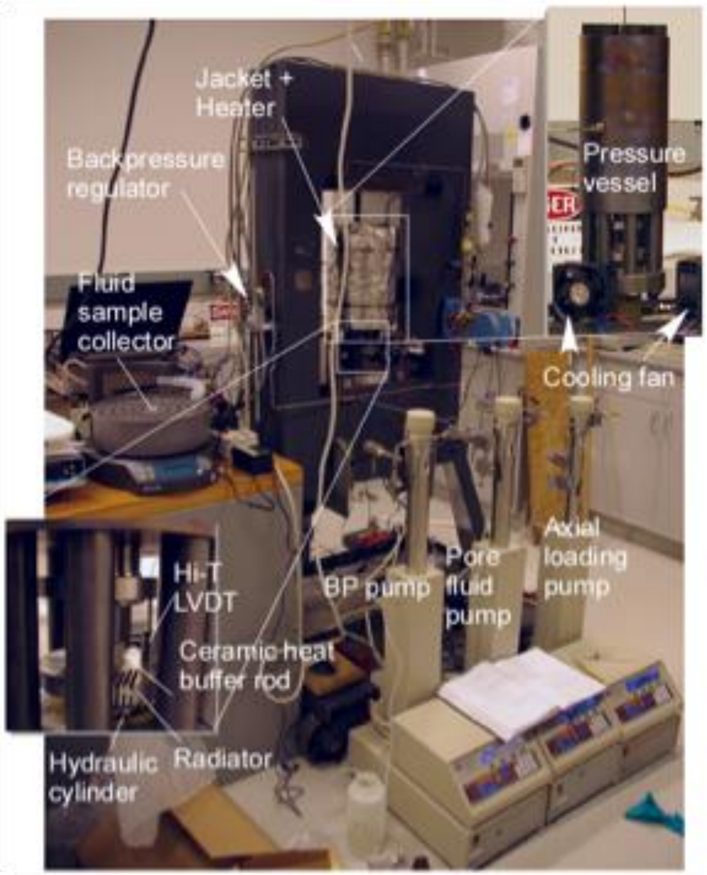


Stripa Granite



Meta-sedimentary rock

- Designed/built custom test chamber and system with:
    1. inert wetted parts
    2. up to 2 inch (5 cm) diameter samples
    3. 2000 psi (13.8 MPa) fluid pressure
    4. 3000 psi (21 MPa) or more normal stress
    5. ability to quantify rock/fracture deformation
    6. minimal dead spaces
    7. appropriate seal types
    8. custom manufactured heaters



Accomplishments, Results and Progress

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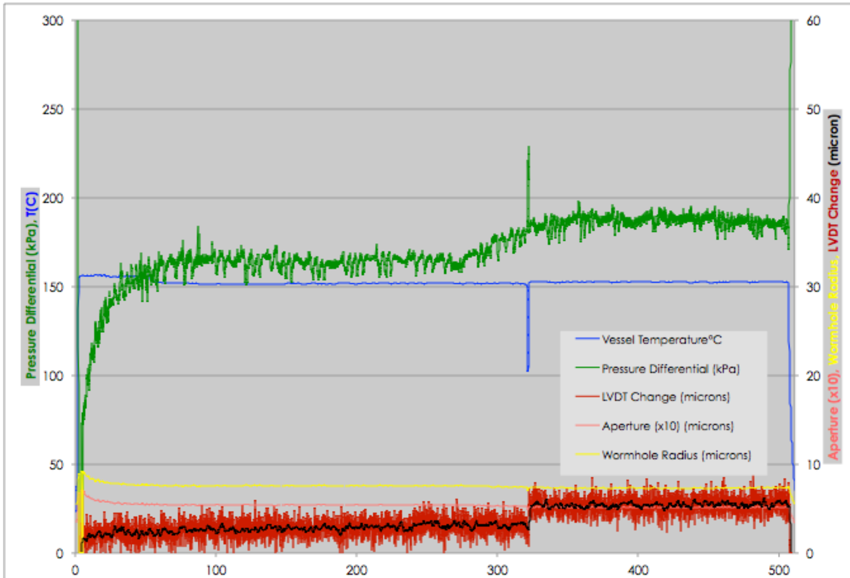
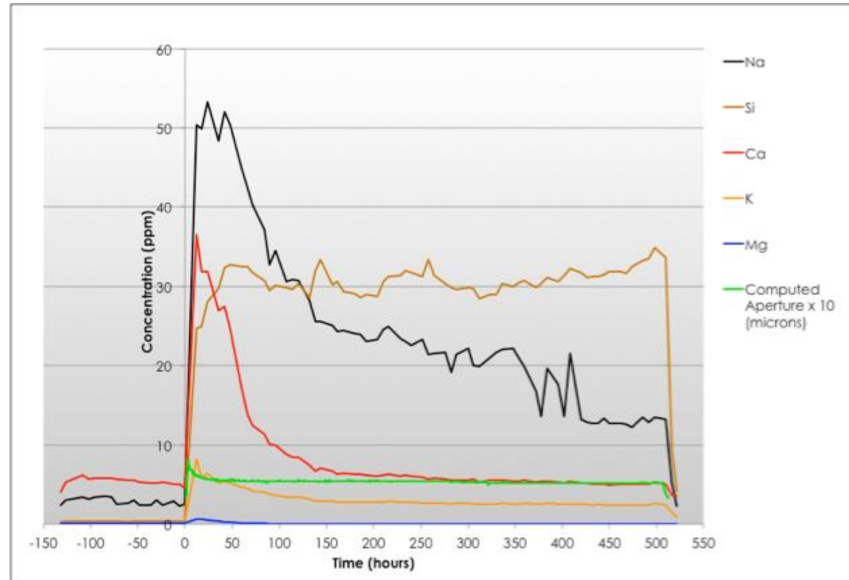
- Created a novel laboratory device to introduce a tensile fracture perpendicular to the core axis in a cylindrical rock core.
- Collected relevant samples courtesy of Ormat
- Completed medium-term shakedown test, additional rock preparation
- Performing fracture sustainability tests including monitoring hydraulic aperture and sample (aperture) deformation.
- Applying surface profilometry for aperture computation
- Data analysis is underway

Rock from Brady, Desert Peak
Machining by Dave Ruddle, LLNL

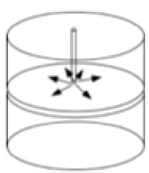
Accomplishments, Results and Progress



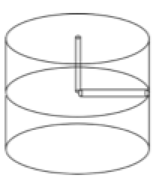
Differential pressure, temperature, computed aperture, deformation



Major cations

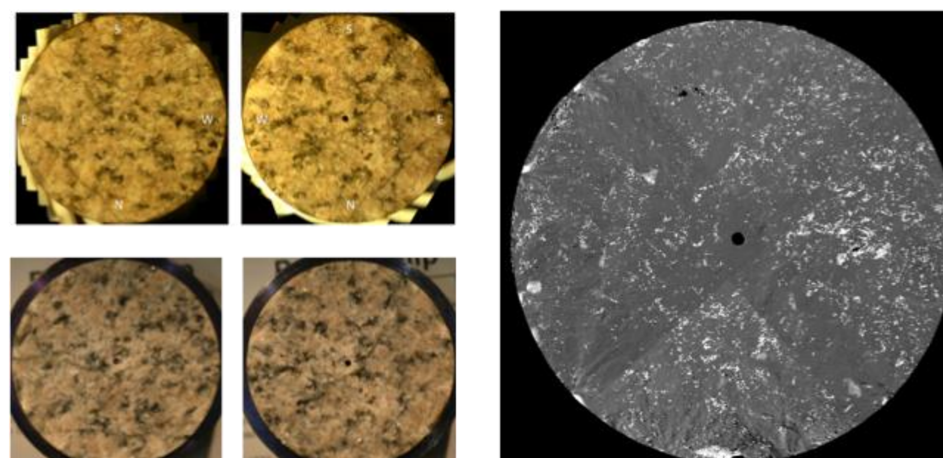


$$h = \left(\frac{6 q \mu \ln\left({r_e}/{r_w}\right)}{\pi (p_e - p_w)} \right)^{1/3}$$



$$R = \left(\frac{8 q \mu (r_e - r_w)}{\pi (p_e - p_w)} \right)^{1/4}$$

Aperture computation from differential pressure



Before (top), after (bottom) and difference in bottom face

Accomplishments, Results and Progress

- We have developed and constructed a custom experimental apparatus capable of applying the EGS conditions needed to study fracture sustainability for an applied normal stress.
  - Unlike Hassler-cell systems, we can directly measure sample deformation.
  - Our apparatus does not require the use of an elastomer sleeve, and minimizes elastomer usage.
  - Our system allows for testing up to 300^{o}C
- We have obtained relevant samples, shared them with our LLNL collaborators, and prepared them for tests.
- We have designed and built a tool to induce tensile fractures in our hockey-puck shaped samples.
- We have performed a number of sustainability tests, increasing in difficulty, and tests are currently in progress.
- We are evaluating data from tests already performed.
- We are evaluating experiment process changes to extend test conditions.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Report in the form of a conference or journal paper describing tests and results.	Submission of Stanford Geothermal Workshop paper. Kneafsey, T. J., Nakagawa, S., Dobson, P. F., & Kennedy, B. M. (2015). *Fracture Sustainability in EGS Systems – Results of Laboratory Studies*. Paper presented at the Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.	January, 2015
Report in the form of a conference or journal paper describing tests and results for all tests.	***Submission of paper to Stanford Geothermal Workshop expected in early 2016 in parallel with journal paper***	***To be completed following test completion***

Future Directions

- Finish test sequence and all analyses, analyze data, write journal paper.
- Complete numerical modeling of at least one test (hopefully all) and compare numerical and experimental results.
- Evaluate possibility of performing additional experiments applying different conditions (influent chemistry).

- Evaluate Fracture Sustainability in terms of the larger question of Reservoir Sustainability looking towards designing and refining appropriate tests for the FORGE site.

Milestone or Go/No-Go	Status & Expected Completion Date
Completion of all currently planned tests and analyses	*July - August, 2015*
Complete numerical modeling of at least one test	*August - September, 2015*
Write up test results and model results for publication	*September - December 2015*

Summary Slide

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- In this project, we are experimentally and numerically evaluating fracture sustainability *at conditions relevant to EGS*, as a subset of reservoir sustainability.
- We have designed, constructed, and are using a novel custom apparatus and system to test fracture sustainability.
- We have resolved numerous issues in performing our test sequences and have presented our successes *and hard knocks* to the geothermal community.
- Our test results are providing a testing ground for numerical simulators, providing an understanding of extending our results to different conditions.