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Fracture Stimulation and Chilled-water Circulation Through Deep Crystalline Rock: Characterization, Modeling, Monitoring, and Heat-transfer Assessment

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ABSTRACT

The EGS Collab Project, sponsored by the U.S. DOE Geothermal Technologies Office, is performing simulations and stimulations in a deep underground laboratory to increase the understanding needed to efficiently implement enhanced geothermal systems (EGS). In Experiment 1, we created an underground test bed at the Sanford Underground Research Facility (SURF) in Lead, SD at a depth of approximately 1.5 km to examine hydraulic fracturing in crystalline rock. Our host rock at this location – phyllite – was well-characterized using numerous field-based geophysical and geological techniques, and laboratory testing. We densely instrumented the test bed, consisting of an injection well, a production well, and six monitoring wells, to allow careful monitoring of stimulation events, and performed long-term flow tests. We performed long-term ambient temperature water injection tests, and as an analog to EGS we performed chilled-water injection tests. System changes resulting from these water injections were monitored using geophysical techniques, flow and pressure measurements, tracer tests, and changes in microbiology. Numerical simulations have been key in providing guidance to experiment design questions, to forecast fracture propagation trajectories and extents, and to interpret processes from the measurements.

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Hydraulic stimulations were effective at connecting our injection and production wells via hydraulic and natural fractures. Several monitoring techniques showed residual displacements and changes in the fracture network over the course of the tests. Injection pressures required to maintain a constant injection rate rose over the duration of the tests; however, sharp pressure declines resulting from even momentary flow disruptions resulted in less pressure required to flow water at the same rate. Thermoelastic effects were clearly observed when temperature changes in the injected water occurred.

The testbed for Experiment 2 is currently being prepared at a depth of about 1.25 km at SURF, and is aimed at investigating shear stimulation. The second testbed is in amphibolite and is subjected to different stress conditions than those in Experiment 1. We have drilled a horizontal and a vertical borehole to aid in testbed understanding, and have performed a number of measurements to characterize the test bed. These include borehole logging, 18 stress tests including 10 using the SIMFIP tool, and extensive fracture mapping of the drift walls and the boreholes. Numerical simulation has been used to forecast fracture propagation trajectories considering the uncertainty in the stress orientations and magnitudes.

1. INTRODUCTION

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as an energy resource supporting the energy security of the United States. Estimates exceed 500 GWe for the western US, surpassing the resource base hosted by conventional hydrothermal systems [*Williams et al.*, 2008]. EGS Resource estimates for the entire United States range up to an order of magnitude larger [*Augustine*, 2016]. Implementing EGS will require (1) improving the understanding and efficacy of stimulation techniques under appropriate in-situ conditions allowing communication among multiple wells, (2) improving imaging and monitoring techniques for permeability enhancement and evolution, as well as associated microseismicity, (3) improving technologies for zonal isolation for multistage stimulations under elevated temperatures, (4) developing technologies to isolate zones for controlling fast flow paths and control early thermal breakthrough, and (5) developing scientifically-based long-term EGS reservoir sustainability and management techniques.

The EGS Collab project aims to refine our understanding of rock mass response to stimulation using accessible deep rock. We are performing 10 m spatial scale experiments under stress relevant to EGS. Our tests and analyses support validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches. We are also testing and improving conventional and novel field monitoring tools. We focus on understanding and predicting permeability enhancement and evolution in crystalline rock, including how to create sustained and distributed permeability for heat extraction from a reservoir by generating new fractures that complement existing fractures. The project has planned three multi-test experiments to increase understanding of 1) hydraulic fracturing (Experiment 1- field tests completed at the time of this writing), 2) shear stimulation (Experiment 2 – testbed construction underway), and 3) other stimulation methods in Experiment 3. Each series of tests within an experiment begins with modeling to support experiment design, and post-test modeling and analysis are performed to examine the effectiveness of our modeling and monitoring tools and approaches. By doing this, we can gain confidence in and improve the array of modeling and monitoring tools in use.

2. EXPERIMENT 1

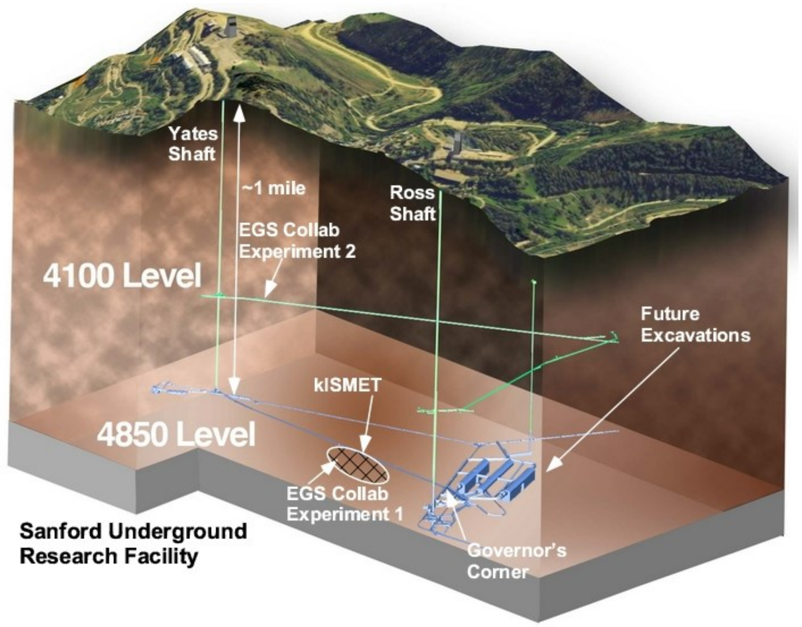
Experiment 1 [*Kneafsey et al.*, 2020] was performed on the 4850 (feet deep) level at the Sanford Underground Research Facility (SURF, Figure 1) in Lead, South Dakota [*Heise*, 2015]. Experiment 1 was intended to establish a fracture network that connects an injection well and a production well using hydraulic fracturing [*Morris et al.*, 2018b]. A schematic of the Experiment 1 testbed is shown in Figure 2. All boreholes for the experiment are nominally 60 meters long, drilled subhorizontally, and were continuously cored. The injection and production boreholes (green and red lines in Figure 2) were drilled approximately parallel to the minimum principal stress direction so that hydraulic fractures would tend to propagate orthogonally to the injection well. The local stress regime is based on kISMET project characterizations in adjacent rock shown in the orange boreholes [*Oldenburg et al.*, 2017; *Wang et al.*, 2017]. Six monitoring wells (yellow in Figure 2) were drilled and instrumentation was grouted in. In general, boreholes were characterized using optical and acoustic televiewers, full waveform sonic, electrical resistivity, natural gamma, and temperature/conductivity logs.

The Experiment 1 test block was well-characterized using many techniques including seismic tomography, electrical resistance tomography (ERT), and extended hydrologic characterization including tracer tests (for details and references see Kneafsey et al. [2020]). Passive seismic monitoring, continuous active source seismic monitoring (CASSM), dynamic ERT imaging using high contrast fluids, acoustic emissions, and distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), strain (DSS) changes, and tracer tests were used to monitor flow and stimulation tests, and fracture aperture strain monitoring was performed using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool. Laboratory investigations provided additional process understanding. With the exception of very large data sets, all data collected and analyzed are stored on a data storage collaboration space (EGS Collab Open EI site) in preparation for inclusion in DOE's Geothermal Data Repository where they are publicly available. Project papers describing individual methods, test results, and simulations can be found on the EGS Collab wiki, Google Scholar (author: EGS Collab) and the Geothermal Data repository[†]. Large data sets, for example microseismic data, are available through the authors.

[†] EGS Collab wiki: https://openei.org/wiki/EGS_Collab_Papers

EGS Collab Google Scholar index: https://scholar.google.com/citations?user=h-rd4hkAAAAJ&hl=en.

Geothermal Data Repository link: https://gdr.openei.org/egs_collab



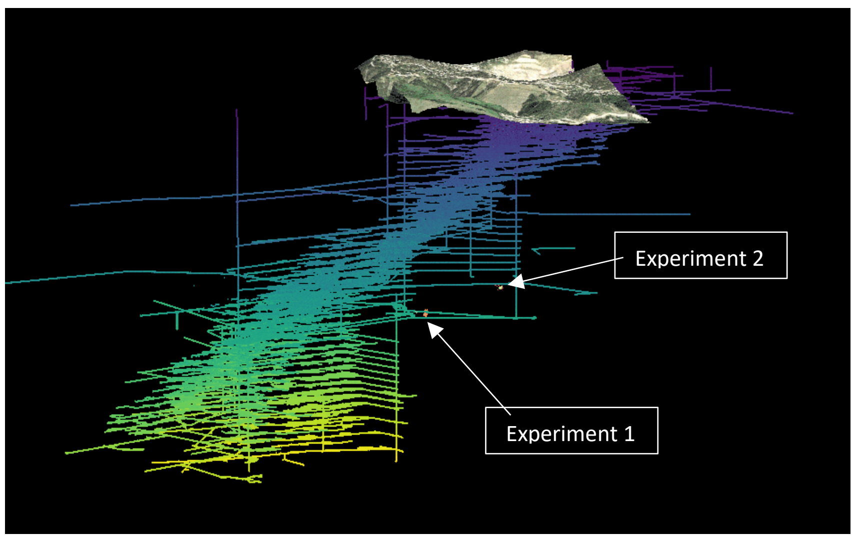


Figure 1: Top - Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, the location of the kISMET experiment, and Experiments 1 and 2. Bottom – spatial relationship between EGS Collab testbeds and former mine workings.

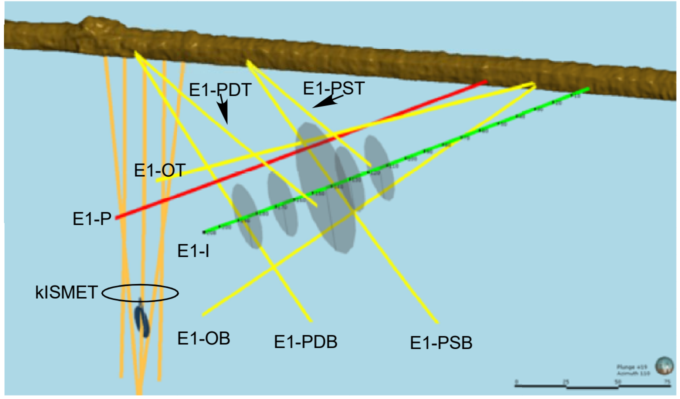


Figure 2: Schematic of wells for Experiment 1 along the West Drift on the 4850 level of SURF. The green line represents the stimulation (injection) well (E1-I), the red line represents the production well (E1-P), yellow lines represent monitoring wells, and orange lines represent kISMET wells. The two monitoring wells originating between E1-I and E1-P – rightmost intersection with the brown drift are called OT ("O" for orthogonal to the anticipated hydraulic fracture and "T" for top) and OB ("B" for bottom), the 2 monitoring wells originating midway down-drift are called PST and PSB ("P" for parallel to the anticipated fracture plane, "S" is for shallow), and the most distant monitoring wells are called PDT and PDB where the "D" is for deep. Orientation of stimulation and production boreholes is approximately parallel to S_{hmin} and the gray disks indicate nominal hydraulic fractures.

2.1 Numerical modeling in Experiment 1

We performed numerical simulations to: 1) support or refine experimental designs, 2) estimate the magnitudes of the effects of the applied stimuli to obtain approvals to proceed, 3) forecast outcomes of operational changes, and 4) provide an understanding of observed behaviors. Key to the project is evaluating the capabilities of the modern state-of-the-art simulators to address project problems. Their ability to accurately predict stimulation, fracture networks, and subsequently thermal energy recovery aids in building confidence in their future applications.

<u>Numerical modeling prior to Experiment 1 investigated:</u>

- the anticipated number and magnitudes of seismic events during hydraulic stimulation [*Huang et al.*, 2018; *Zhou et al.*, 2018a]
- the thermal profile and induced stress profile in the testbed [*Fu et al.*, 2018; *White et al.*, 2019]
- the fracture geometry from the well; requirement for borehole notching [*Fu et al.*, 2018; *White et al.*, 2019]
- the impact of notch geometry on stimulation pressure and near wellbore impedance [*Fu et al.*, 2018; *White et al.*, 2019]
- estimating the preferred orientation for the stimulation borehole to meet the project objectives [*Knox et al.*, 2017; *Morris et al.*, 2018a]
- identifying flow rates and pressures to perform the circulation experiments to prevent fracture propagation [*White et al.*, 2017]
- determining the circulation duration required to achieve measurable temperature changes in the production borehole [*White et al.*, 2017; *Zhang et al.*, 2018]
- use of the production well serve to prevent fracture propagation to the drift [*Frash et al.*, 2018a; *Frash et al.*, 2018b; *White et al.*, 2018]
- estimating the anticipated fracture shape and arrival time in terms of injected fluid volume of the hydraulically generated fracture under the mechanically and thermally altered stress state [*Fu et al.*, 2018; *Morris et al.*, 2018a; *White et al.*, 2018]

Confidence in numerical simulation was built by modelers participating in the detailed experiment design. The project supported the expert use of codes selected to incorporate known processes to the extent reasonable. The modelers also had an excellent understanding of the processes modeled. Simulations were performed in near-real-time, using models that were constructed and enhanced over time. These yielded reliable, high-quality solutions. The key to fast simulation turnarounds was to begin with building high-quality baseline models in the experiment design phase and incorporate new observations and parameters over time.

It was understood that exact predictions and exact matches were not be expected. The modeling was intended to be used to provide best-estimate predictions, and to try to understand the magnitude of processes. Heterogeneities in the rock fabric, presence and effects of natural fractures, spatial variations of in-situ stress, and other geologic features generally preclude numerical simulation from providing exact matches to experimental outcomes. The true value of numerical simulation comes from the understanding it provides revealing complex system behavior, allowing scientists and engineers to make informed choices about experimental designs and interpreting empirical observations. Experiment 1 yielded a number of experimental observations that at first consideration seemed counter-intuitive, such as temperature spikes at fracture/monitoring borehole intersections, water production in monitoring boreholes beyond the production borehole, sharp pressure drops after injection interruptions, and rapid tracer breakthrough but very slow thermal breakthrough. In each case numerical simulation either provided rational explanations for the observations, or ruled out hypotheses. An example of some of these modeling studies is presented below.

Example: Tracer and Controlled-Temperature Fluid Injection - Tests and Modeling

Although injection flow rate, pressure, and water recovery rate provide important information on the Experiment 1 testbed performance, chemical tracers provide additional information such as changes in the fracture system between the injection and production wells. Rhodamine-B, fluorescein, C-dots, and phenyl acetate were used as fluorescing tracers and Cl, Br, and K were used as ionic tracers [*Mattson et al.*, 2019a]. These tracers were used in different combinations to evaluate the fracture pathway changes during injection testing, cold water injection, and chemical manipulation of the injection water. Synthetic deoxyribose nucleic acid (DNA) tracers were used during the early tracer works; however, their use was subsequently discontinued because of poor recovery. All tracer cocktail solutions injected into the testbed included at least one fluorescing tracer allowing near-real-time detection in the drift and rapid decision-making during field operations.

Over the period from 10/24/2018 through 02/03/2020 a total of 21 tracer tests were conducted [*Mattson et al.*, 2019a; *Mattson et al.*, 2019b; *Neupane et al.*, 2020; *Neupane et al.*, 2019]. In general, total tracer recoveries in terms of mass balance were in the 30% range, while volumetric water recoveries generally increased over time to nearly 98% by the conclusion of the long-term chilled-water test. For the C-dots, arrival times for peak concentrations at one location in the production borehole varied between 1.4 and 6.9 hours, and at a nearby location varied between 0.8 and 5.7 hours during the long-term chilled-water test. This result is in sharp contrast to the near negligible change in temperature measured over the course of the many months long-term chilled-water test.

Simulations were executed to understand the contrast in tracer and thermal breakthroughs observed in the long-term chilled-water test [*Jafarov et al.*, 2020; *Wang et al.*, 2018; *White et al.*, 2020; *Winterfeld et al.*, 2019; *Wu et al.*, 2019a; *Wu et al.*, 2020a; *Wu et al.*, 2019b; *Wu et al.*, 2021; *Wu et al.*, 2019c; *Wu et al.*, 2020b; *Zhou et al.*, 2018a; *Zhou et al.*, 2018b]. The general finding from all of these studies was that the relatively high thermal conductivity of the phyllite caused rapid rock/water temperature equilibration resulting in little thermal breakthrough, even with rapid chemical breakthrough. These studies also showed that a significant portion of the fracture is available for heat transfer and there is no evidence of extreme short circuiting under the applied conditions. The possibility that the recovered fluid was diluted by other formation waters cannot be eliminated, however, implying that while we achieved close to a 90 percent fluid balance (our volumetric fluid recovery was approximately the same as our injection), the system was not closed [*Zhang et al.*, 2020].

2.2 Modeling Challenges

There are many modeling challenges in simulating fracture flow and heat extraction. Understanding the interplay between poroelastic, thermal, chemical, and biological processes has been identified as important for interpreting injection-pressure data. The stimulated and natural fracture network controls fluid flow and heat exchange with the low permeability rock matrix; characterizing the fracture network based on field observations is critical for developing realistic flow models [*Makedonska et al.*, 2020; *Roggenthen and Doe*, 2018; *Schwering et al.*, 2020]. The rates at which chemistry may impact flow can be surprisingly fast, complicating injectivity data interpretation. Another challenge is modeling a dynamic system. In Experiment 1, the flow rates at the several locations where water was collected changed over time. Additional observations and data would be needed to identify the causes. Experiment 1 taught the modeling community that every element in the suite of THMC processes needs to be considered to understand the dynamic and unpredictable nature of EGS reservoirs. Quite often EGS reservoirs are conceptualized as TH systems, which might be sufficient for design, prototyping, or optimization studies, but truly understanding the more challenging observed behaviors of a particular reservoir requires full coupling of all the processes, and *full coupling of modeling expertise* across these processes.

Application of these simulation tools to EGS with elevated temperatures will require additional stepwise confidence-building in the hands of experienced modelers knowledgeable of the processes requiring consideration. Experiment 1 was especially challenging in evaluating the ability of the numerical simulation tools to predict thermal recovery for three reasons: 1) the relatively low flow rates, 2) the relatively high thermal conductivity of the matrix rock, and 3) the thermal gradients created by cooling the experimental volume over a 50-year mining period. Nevertheless, the simulators were able to accurately reproduce the observed nearly constant production temperature over the course of the 196-day chilled-water circulation test. We anticipate commercial-scale applications, such as FORGE, to yield stronger temperature differences and signals for comparisons against simulation tools.

Example: Increased Flow Resistance over the Course of Experiment 1

In the long-term chilled-water test, injection pressure slowly increased over the course of the test (Figure 3). The underlying causes of this pressure increase over time and significant decrease in injection pressure following a flow interruption have not been determined. One hypothesis to explain the steady rise of injection pressure is that they are the result of poroelastic effects, with fines, geochemical, and biological plugging being other hypotheses suggested [*Kneafsey et al.*, 2020]. The observed pressure rise could also indicate a gradual filling of a fracture network within a quasi-closed volume of rock thereby increasing the local matrix pore pressure and resulting in increased normal stress on the fractures and a reduced aperture. The poroelastic, geochemical, and biological hypotheses all explain a reduction in fracture aperture, which yields increased flow resistance. At a constant injection rate, this results in increased injection pressures, matching the experimental observation. One indication of this is the reduced overall leakoff over time, which is indicated by the increase in volumetric water recovery during the test. Increasing injection pressure over time could lead to pressures that exceed the fracture propagation pressure, which was not desirable for the project such that the continuous propagation of the fracture to the drift would have halted the experiment.

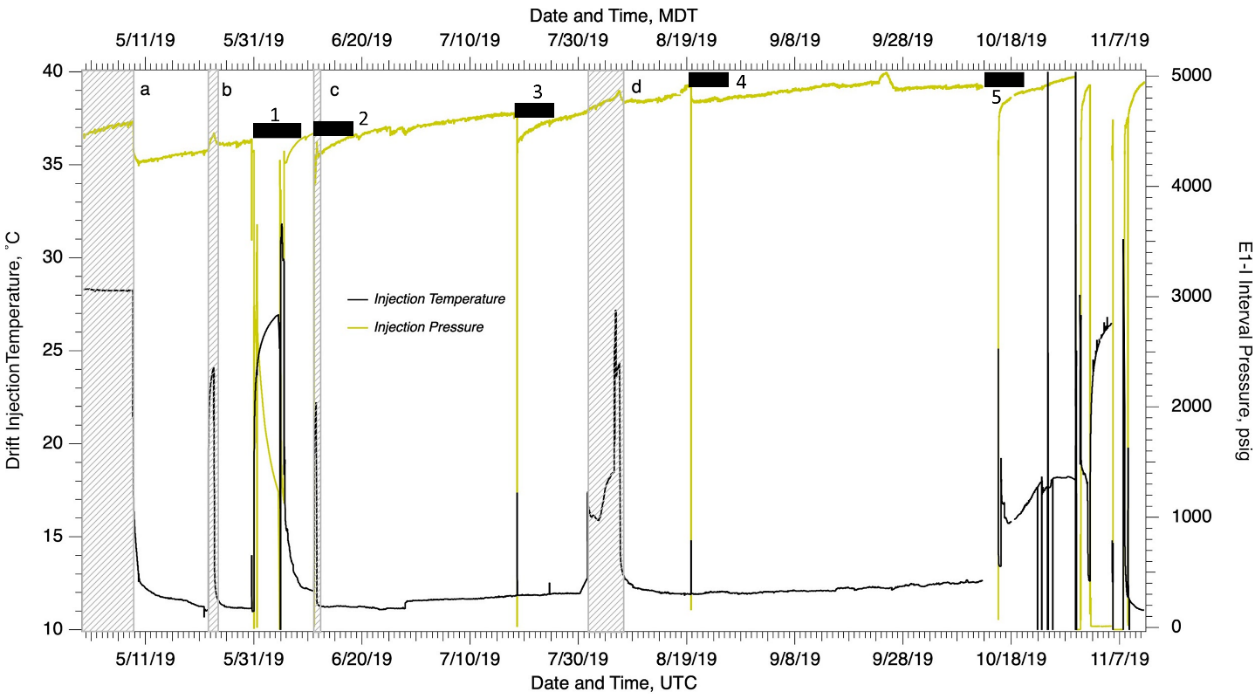


Figure 3: Temperature of the water injected at the borehole collar (black curve) and E1-I interval pressure (yellow curve) versus time. The markers "a" through "d" represent the period of interruptions in operation of the water chiller, and the markers "1" through "5" represent the interruptions in pumping and interval pressure response upon resumptions of pumping.

To understand the observed increased flow resistance across the fracture network, and to provide insight to observed sharp drops in flow resistance when injection pumping was momentarily to temporarily halted, *White and Burghardt* [2021] coupled geomechanics (i.e., thermal-hydrological-mechanical (THM) coupling) with the embedded borehole and fracture modeling approach. This coupling allowed them to investigate the dynamic behavior of the fracture aperture - and thus flow resistance - in response to changes in matrix rock temperature and pore pressure. Their analysis questioned whether increased poroelastic stress on the hydraulic fracture, resulting from leakoff, could explain the gradual rise in flow resistance over the course of the test. Simulation results were generated for a number of cases with different matrix permeability values. Gradually increasing injection pressures, as observed in the experiment, were indicated; however, the matrix permeabilities required to generate this response were outside the range of measured permeabilities of the host phyllite rock. These simulations did not consider the full complexities of the poroelastic mechanics. In spite of that, they suggested that something other than increased poroelastic stress causes the gradual increase in injection pressure over time.

2.3 Learnings from Experiment 1

Poroelasticity may play an important role in the response of the rock-fracture system to fluid circulation; however, additional evaluation is needed. Two significant thermoelastic effects have been observed on this project: 1) from the cooling of the mine drift over decades and 2) from the injection of cool water into the warm fractured rock. Fracture growth from stimulations on the 4850-level proceeded in the direction predicted (towards the drift), providing an element of validation of the thermoelastic effect. Additional stress testing at varying distance from the drift may help support that validation. Injection of chilled water during the flow test initially resulted in an increase in permeability. Following this increase, the permeability decreased consistent with other observations. This effect should be expected at FORGE and in EGS systems where cooler water will be introduced into hot rock.

Local geology was observed to affect stimulation and flow behavior. kISMET drilling (with near vertical boreholes) showed few fractures. Nearby EGS Collab drilling (with subhorizontal boreholes) identified many fractures, particularly in the lower regions of the test bed. Electrical resistance tomography data showed the geologic complexity was greater than anticipated [*Johnson et al.*, 2019]. Analysis of campaign seismic data revealed that the rock is likely a horizontal transverse isotropic (HTI) medium [*Gao et al.*, 2020]. Stress measurements from a vertical borehole on the 4100 level highlights effects of local geology as well, particularly the presence of a rhyolite body on the 4100 level having a lower minimum principal stress than the amphibolite strata above and below it. Careful characterization is needed to understand the local geology and its effect on local stress and fluid flow.

The role of natural fractures can be estimated a-priori if enough information including stress and fracture orientations can be determined by characterization [*Singh et al.*, 2019]. Discrete fracture network models graphically summarize this information, making interpretation of stimulation behavior more tractable [*Schwering et al.*, 2020].

Several methods of quantifying fracture opening and closure have been demonstrated in the EGS Collab project. Continuous active source seismic monitoring spatially imaged fracture opening in the monitored region [*Ajo-Franklin et al.*, 2018; *Chi et al.*, 2020; *Kneafsey et al.*, 2019]. The SIMFIP tool was also used to quantify rock motion across a fracture or fractured zone [*Guglielmi et al.*, 2021; *Kneafsey et al.*, 2019] in a borehole during stimulation, and in a number of stimulations in a vertical borehole on the 4100 level. ERT results are being used to interpret geomechanical changes including fracture opening and closure (Johnson et al. 2021 in preparation). These quantifications provide key insights into stimulation.

3. EXPERIMENT 2

Experiment 2, intended to investigate shear stimulation, will be performed on the 4100 (foot depth, ~1.25 km) level at SURF. The rock investigated is the Yates amphibolite and the subsurface stress conditions are different from those on the 4850 level [*Ingraham et al.*, 2020]. Pre-test investigation of the 4100 level included mapping fractures and features that can be observed on the drift walls, and the drilling and logging of a 10 m horizontal borehole and a 50 m vertical borehole. The vertical borehole identified and penetrated a thick (~11 m) rhyolite layer. Eighteen stress tests have been performed in the vertical borehole and eight of these have used the SIMFIP tool to quantify displacement during testing. Instantaneous shut-in pressures (ISIP) indicating minimum principal stress information can be grouped into 3 categories (Figure 4). In the amphibolite below the rhyolite, ISIP values are around 27.6 MPa (4000 psi). ISIP values in the rhyolite vary around 18.6 MPa (2700 psi). In the upper amphibolite ISIP values vary around 21.4 MPa (3100 psi). Because of this stress heterogeneity, the Experiment 2 test bed is designed to be entirely *above* the rhyolite layer. Cores have been examined and photographed, and distributed for initial laboratory tests. These data feed into concepts to be used in the design of the test bed.

Schematics of the Experiment 2 well layout are shown in Figure 5 and the testbed location is shown in Figure 1. In this testbed, we envision our injection borehole (green) and production borehole(s) (red) to fan out providing different distances between the wells depending on the depth from the collar. The orientations of the injection and production wells were selected to increase the likelihood of intersecting natural fractures that are favorably oriented for shear reactivation. The analysis considered five fracture set orientations identified from the drift wall and borehole observations. The locations of fractures will not be known until drilling is completed. Because of that, it was decided to have multiple production wells surrounding the injection well. In this manner, it can be expected that stimulated fractures will intersect at least one production well. Monitoring wells are oriented to span the volume of interest on as many sides as possible at a larger distance than was used in Experiment 1. Consequently, we have two pairs of monitoring wells oriented approximately orthogonal to the injection well above and below the stimulation zone. One monitoring well, however, is oriented subparallel to the stimulation well. Geophysical sensors used and their deployment in Experiment 2 will be redesigned based on learnings from Experiment 1, although the range of sensors used will be similar to those deployed in Experiment 1.

Extensive simulations of hydraulic stimulations have been performed in Experiment 2's design phase. Although the main research target of Experiment 2 is shear stimulation, we also consider hydraulic fracturing. This is because the outcome of hydraulic shearing depends highly on in situ characteristics of natural fractures known to be highly variable and difficult to measure. Because the uncertainties in the simulation parameters are greater than the value of hydraulic shearing simulations in the design phase, we focused on two simulation tasks that can directly impact testbed design decisions:

1. Predict the propagation trajectory of a potential opening-mode hydraulic fracture.
2. Predict the breakdown pressure in the near-wellbore region for identified natural fractures.

Detailed results on the first simulation task are reported in *Fu et al.* [2021]. Results on the second task will be reported in future publications. Selected key results are shown in Figure 6.

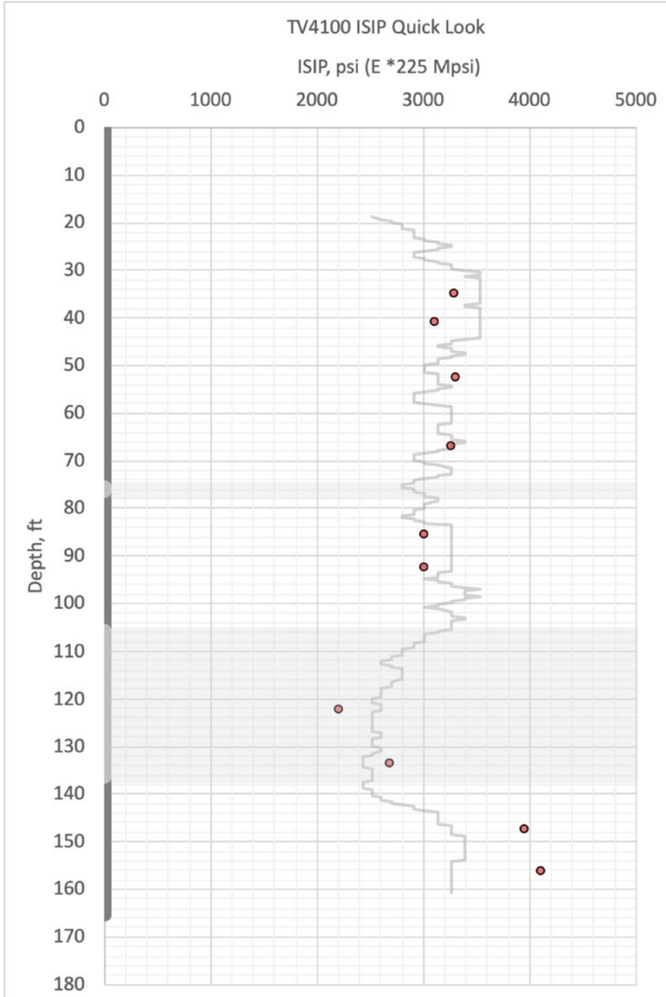


Figure 4. Instantaneous shut-in pressures (red dots) for tests at 10 locations in the 50 m vertical borehole on the 4100 level (no SIMFIP). The grey line is the dynamic Young's modulus from full waveform sonic data, and the shaded bar on the left indicates the rock type encountered (dark = amphibolite, light = rhyolite). Note the high ISIP below the rhyolite, low ISIP in the rhyolite, and moderate relative consistent ISIP above the rhyolite.

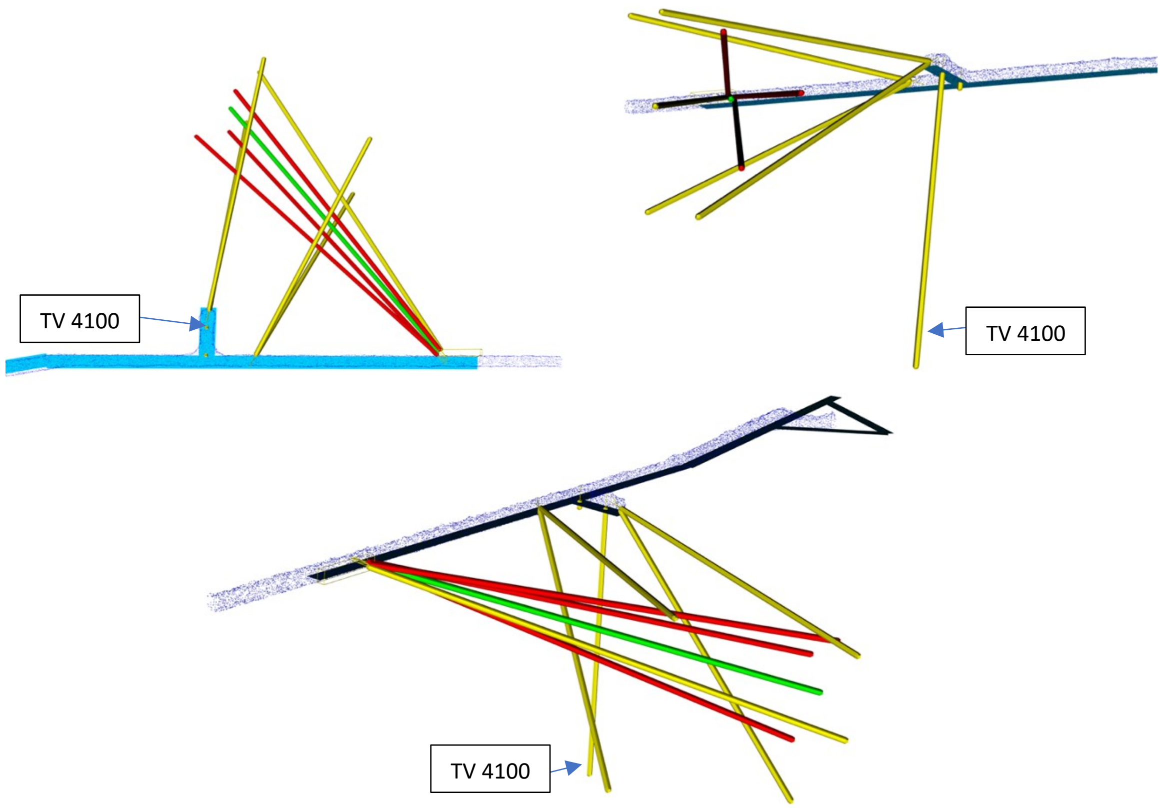


Figure 5. Expected well orientations for Experiment 2, shown from different perspectives (top left – from above; top right – oblique from below; bottom – oblique from the side). The thick blue line represents the drift, the green line represents the injection well, red lines represent production wells, and yellow lines represent monitoring wells. Other than the vertical well TV4100, all wells are subhorizontal.

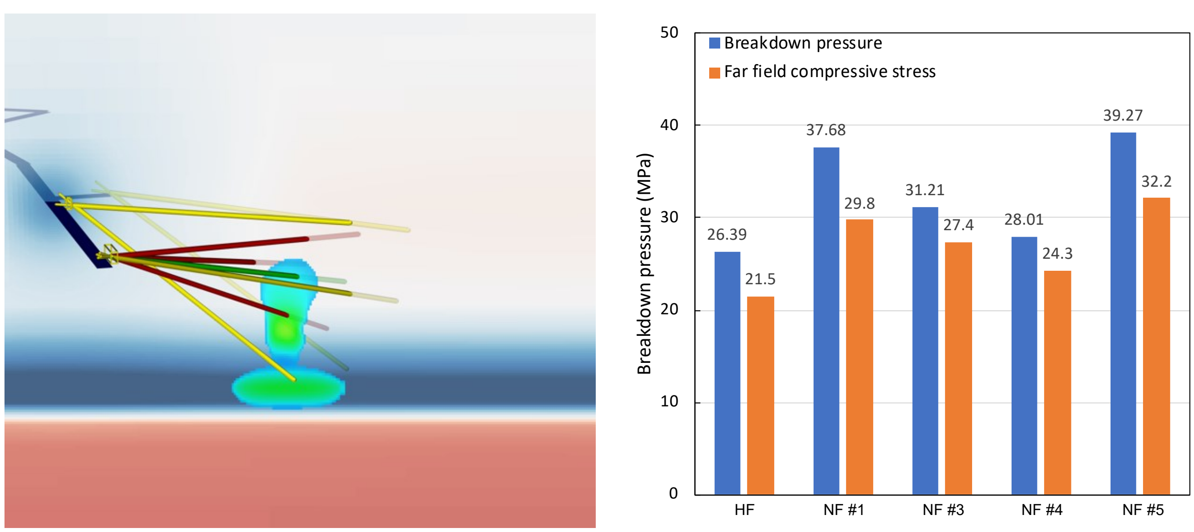


Figure 6. Selected results from stimulation simulations for Experiment 2. The left figure shows the predicted fracture shape if an opening-mode hydraulic fracture is accidentally or deliberately created. The fracture would have a strong tendency to propagate toward the rhyolite layer, which has smaller S_{hmin} than in the amphibolite where the fracture would be initiated. The right figure compares the predicted breakdown pressures among five likely fracture planes as well as with the far-field compressive stresses on these five fracture planes.

4. CONCLUDING REMARKS

EGS Collab Experiment 1 focused on hydraulic fracturing and is now complete. This set of tests has investigated multiple stimulations, and performed long-term flow tests of ambient temperature and chilled water and used tracer tests to help understand flow and transport. The Experiment 1 testbed was well-characterized, and subsequent tests were monitored using many geophysical techniques. Design of the experiment testbed, monitoring systems, and stimulation and flow experiments were performed using modeling results based on state-of-the-art simulation tools. Quality data have been generated, are publicly available, and are being used by geothermal researchers. Numerous papers describing aspects of the tests are also available. The testbed for Experiment 2, focusing on shear stimulation, is now being constructed. Numerical modeling has been used to aid in the design of the experiment and the monitoring system. Some similarities in the testbed layout between the 2 experiments are apparent to take advantage of findings/lessons learned, and differences are apparent for the same reason. Similar monitoring tools to those used in Experiment 1 will be refined and used in Experiment 2. Drilling and core and borehole characterization are expected to occur until late spring of 2021, when the testbed is instrumented. We anticipate that fracture stimulation testing will commence this summer.

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REFERENCES

Ajo-Franklin, J. B., M. Schoenball, T. Wood, M. Robertson, P. Petrov, L. Huang, . . . EGS Collab Team (2018), Imaging Hydraulic Fracture Propagation Using Semi-Permanent Continuous Active Seismic Source Monitoring: Results from the DOE EGS Collab Experiment, paper presented at American Geophysical Union Fall Meeting 2018, American Geophysical Union, Washington DC, December 12, 2018.

Augustine, C. (2016), Update to Enhanced Geothermal System Resource Potential Estimate, *GRC Transactions*, *40*, 6.

Chi, B., L. Huang, K. Gao, J. Ajo-Franklin, T. J. Kneafsey, J. Hampton, and EGS Collab Team (2020), Anisotropic Imaging of Created Fractures in EGS Collab Experiments Using CASSM Data, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Frash, L. P., K. Arora, Y. Gan, M. Lu, M. Gutierrez, P. Fu, . . . EGS Collab Team (2018a), Laboratory Validation of Fracture Caging for Hydraulic Fracture Control, paper presented at 52nd U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, Seattle, Washington, 2018/8/21.

Frash, L. P., P. Fu, J. Morris, and EGS Collab Team (2018b), Fracture Caging: Can We Control the Extent of a Hydraulic Fracture Stimulated Zone?, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-213.

Fu, P., M. White, J. Morris, T. Kneafsey, and EGS Collab Team (2018), Predicting Hydraulic Fracture Trajectory Under the Influence of a Mine Drift in EGS Collab Experiment I, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Fu, P., H. Wu, J. P. Morris, P. C. Schwering, C. Ulrich, and EGS Collab Team (2021), Simulating Hydraulic Fracture Stimulations at the EGS Collab: Model Validation from Experiments 1 and Design-Phase Simulation for Experiment 2, paper presented at 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Gao, K., L. Huang, H. A. Knox, P. C. Schwering, C. R. Hoots, J. Ajo-Franklin, . . . EGS Collab Team (2020), Anisotropic Elastic Properties of the First EGS Collab Testbed Revealed from the Campaign Cross-Borehole Seismic Data, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Guglielmi, Y., P. Cook, F. Soom, M. Schoenball, P. Dobson, and T. Kneafsey (2021), In Situ Continuous Monitoring of Borehole Displacements Induced by Stimulated Hydrofracture Growth, *Geophysical Research Letters*, *n/a*(n/a), e2020GL090782, doi:https://doi.org/10.1029/2020GL090782.

Heise, J. (2015), The Sanford Underground Research Facility at Homestake, *Journal of Physics: Conference Series*, *606*(1), 26.

Huang, H., J. Zhou, E. Mattson, and R. Podgorney (2018), Mechanistically Modeling of Hydraulic Fracture Opening, Closure and Residual Fracture Permeability During Cyclic Flow Injection Tests, paper presented at Geothermal Resources Council 2018 Annual Meeting Geothermal Resources Council Transactions, Reno, NV.

Ingraham, M. D., P. C. Schwering, J. Burghardt, C. Ulrich, T. Doe, W. M. Roggenthen, and C. Reimers (2020), Analysis of Hydraulic Fracturing on the 4100 Level at the Sanford Underground Research Facility, paper presented at 54th U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, 2020/9/18.

Jafarov, E. E., N. Makedonska, S. Karra, R. Pawar, J. Beisman, G. Neupane, . . . EGS Collab Team (2020), Simulations of the 3D Geothermal Heat Flow in Fractured Media, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Johnson, T., C. Strickland, H. Knox, J. Thomle, V. Vermuel, C. Ulrich, . . . EGS Collab Team (2019), EGS Collab Project Electrical Resistivity Tomography Characterization and Monitoring Status, paper presented at 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019.

Kneafsey, T. J., D. Blankenship, P. F. Dobson, J. P. Morris, M. D. White, P. Fu, . . . EGS Collab Team (2020), The EGS Collab Project: Learnings from Experiment 1, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Kneafsey, T. J., D. P.F., J. B. Ajo-Franklin, Y. Guglielmi, C. A. Valladao, D. A. Blankenship, . . . EGS Collab Team (2019), EGS Collab Project: Status, Tests, and Data, paper presented at 53rd US Rock Mechanics/Geomechanics Symposium, New York, NY, USA, 23–26 June 2019.

Knox, H., P. Fu, J. Morris, Y. Guglielmi, V. Vermeul, J. Ajo-Franklin, . . . EGS Collab Team (2017), Fracture and Flow Designs for the Collab/Sigma-V Project, paper presented at GRC Transactions, Vol. 41, 2017.

Makedonska, N., E. Jafarov, T. Doe, P. Schwering, G. Neupane, and EGS Collab Team (2020), Simulation of Injected Flow Pathways in Geothermal Fractured Reservoir Using Discrete Fracture Network Model, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Mattson, E., G. Neupane, A. Hawkins, J. Burghardt, M. Ingraham, M. Plummer, and EGS Collab Team (2019a), Fracture Tracer Injection Response to Pressure Perturbations at an Injection Well, *GRC Transactions*, *43*.

Mattson, E., Y. Zhang, A. Hawkins, T. Johnson, J. Ajo-Franklin, G. Neupane, and EGS Collab Team (2019b), Preliminary Collab Fracture Characterization Results from Flow and Tracer Testing Efforts paper presented at 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019.

Morris, J. P., P. Dobson, H. Knox, J. Ajo-Franklin, M. D. White, P. Fu, . . . EGS Collab Team (2018a), Experimental Design for Hydrofracturing and Fluid Flow at the DOE Collab Testbed, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Morris, J. P., P. Fu, P. Dobson, J. Ajo-Franklin, T. J. Kneafsey, H. Knox, . . . EGS Collab Team (2018b), Experimental Design for Hydrofracturing and Fluid Flow at the DOE EGS Collab Testbed.

Neupane, G., E. D. Mattson, M. A. Plummer, and EGS Collab Team (2020), Results of Multiple Tracer Injections into Fractures in the EGS Collab Testbed-1, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Neupane, G., R. K. Podgorney, H. Huang, E. D. Mattson, T. J. Kneafsey, P. F. Dobson, . . . EGS Collab Team (2019), EGS Collab Earth Modeling: Integrated 3D Model of the Testbed, *GRC Transactions*, *43*, 21.

Oldenburg, C. M., P. F. Dobson, Y. Wu, P. J. Cook, T. J. Kneafsey, S. Nakagawa, . . . J. Heise (2017), Hydraulic fracturing experiments at 1500 m depth in a deep mine: Highlights from the kISMET project, paper presented at 42nd Workshop on Geothermal Reservoir Engineering, Stanford University.

Roggenthen, W. M., and T. W. Doe (2018), Natural Fractures and Their Relationship to the EGS Collab Project in the Underground of the Sanford Underground Research Facility (SURF), paper presented at 52nd U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, Seattle, Washington, 2018/8/21.

Schwering, P. C., T. W. Doe, W. M. Roggenthen, G. H. Neupane, H. Johnston, P. F. Dobson, . . . C. Reimers (2020), Deterministic Discrete Fracture Network (DFN) Model for the EGS Collab Project on the 4850 Level of the Sanford Underground Research Facility (SURF), paper presented at 54th U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, 2020/9/18.

Singh, A., M. Zoback, P. F. Dobson, T. J. Kneafsey, M. Schoenball, Y. Guglielmi, . . . EGS Collab Team (2019), Slip tendency analysis of fracture networks to determine suitability of candidate testbeds for the EGS Collab hydroshear experiment, *Geothermal Resources Council Transactions*, *43*, 405–424.

Wang, C., P. Winterfeld, B. Johnston, and Y.-S. Wu (2018), An Embedded 3D Fracture Modeling Approach for Simulating Fracture-Dominated Fluid Flow and Heat Transfer in Geothermal Reservoirs, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Wang, H. F., M. Y. Lee, T. W. Doe, B. C. Haimson, C. M. Oldenburg, and P. F. Dobson (2017), In-Situ Stress Measurement at 1550-Meters Depth at the kISMET Test Site in Lead, S.D, paper presented at 51st U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, San Francisco, California, USA, 2017/8/28/.

White, M., P. Fu, H. Huang, A. Ghassemi, and EGS Collab Team (2017), The Role of Numerical Simulation in the Design of Stimulation and Circulation Experiments for the EGS Collab Project paper presented at GRC Transactions, Vol. 41, 2017

White, M., T. Johnson, T. Kneafsey, D. Blankenship, P. Fu, H. Wu, . . . EGS Collab Team (2019), The Necessity for Iteration in the Application of Numerical Simulation to EGS: Examples from the EGS Collab Test Bed 1, paper presented at 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019.

White, M. D., J. A. Burghardt, and EGS Collab Team (2021), Modeling the Dynamic Flow Resistance Across the Fracture Network of EGS Collab Experiment 1, paper presented at 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA, February 15-17, 2021.

White, M. D., P. Fu, and EGS Collab Team (2020), Application of an Embedded Fracture and Borehole Modeling Approach to the Understanding of EGS Collab Experiment 1, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

White, M. D., P. Fu, A. Ghassemi, H. Huang, J. Rutqvist, B. Johnston, and EGS Collab Team (2018), Numerical Simulation Applications in the Design of EGS Collab Experiment 1, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Williams, C. F., M. J. Reed, R. H. Mariner, J. DeAngelo, and S. P. Galanis, Jr. (2008), Assessment of moderate- and high-temperature geothermal resources of the United States, edited by U. S. G. Survey, p. 4.

Winterfeld, P., B. Johnston, K. Beckers, Y.-S. Wu, and EGS Collab Team (2019), Code Modifications for Modeling Chemical Tracers and Embedded Natural Fractures at EGS Collab, paper presented at 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019.

Wu, H., P. Fu, and J. Morris (2019a), Analysis of hydraulic and thermal characteristics in a fracture network at the EGS Collab experiment through tracer and thermal modeling, paper presented at AGU Fall Meeting 2019, AGU.

Wu, H., P. Fu, and J. P. Morris (2020a), Predicting thermal responses at the EGS Collab testbed based on tracer test-inferred flow fields, paper presented at 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020.

Wu, H., P. Fu, J. P. Morris, E. D. Mattson, A. J. Hawkins, Y. Zhang, . . . EGS Collab Team (2019b), Characterizing Fracture Flow in EGS Collab Experiment Based on Stochastic Modeling of Tracer Recovery, paper presented at 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019.

Wu, H., P. Fu, J. P. Morris, E. D. Mattson, G. Neupane, M. M. Smith, . . . T. Kneafsey (2021), Characterization of flow and transport in a fracture network at the EGS Collab field experiment through stochastic modeling of tracer recovery, *Journal of Hydrology*, *593*, 125888, doi:https://doi.org/10.1016/j.jhydrol.2020.125888.

Wu, H., P. Fu, J. P. Morris, R. R. Settgast, F. J. Ryerson, E. D. Mattson, . . . Y. Zhang (2019c), Stochastic modeling of a conservative tracer test for the characterization of fracture flow patterns in EGS Collab Experiment 1, paper presented at 53rd US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, New York, NY, USA, 23–26 June 2019.

Wu, H., P. Fu, J. Zhang, and J. P. Morris (2020b), Interpretation of Tracer Data Using a Markov Chain Monte Carlo Approach for the Characterization of the EGS Collab Testbed, paper presented at 54th U.S. Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, 2020/9/18.

Zhang, Y., A. E. Dekas, A. J. Hawkins, A. E. Parada, O. Gorbatenko, K. Li, and R. N. Horne (2020), Microbial Community Composition in Deep-Subsurface Reservoir Fluids Reveals Natural Interwell Connectivity, *Water Resources Research*, *56*(2), e2019WR025916, doi:https://doi.org/10.1029/2019WR025916.

Zhang, Y., C. Doughty, L. Pan, T. Kneafsey, and EGS Collab Team (2018), What Could We See at the Production Well Before the Thermal Breakthrough?, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Zhou, Q., C. M. Oldenburg, T. J. Kneafsey, and EGS Collab Team (2018a), Modeling Transport of Multiple Tracers in Hydraulic Fractures at the EGS Collab Test Site, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.

Zhou, Q., C. M. Oldenburg, J. Rutqvist, T. J. Kneafsey, and EGS Collab Team (2018b), Analytical and Numerical Modeling of Heat Transport in Fractured Reservoirs, paper presented at 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018.