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### Authors

Kneafsey, T  
Blankenship, D  
Dobson, PF  
[et al.](#)

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# **The EGS Collab Project: Stimulating and Simulating Experiments in Crystalline Rock in An Underground Research Site**

**Tim Kneafsey<sup>1</sup>, Doug Blankenship<sup>2</sup>, Patrick F. Dobson<sup>1</sup>, Joseph Morris<sup>3</sup>, Pengcheng Fu<sup>3</sup>, Mark White<sup>4</sup>, Paul Schwering<sup>2</sup>, Hunter Knox<sup>4</sup>, Yves Guglielmi<sup>1</sup>, Martin Schoenball<sup>1</sup>, Jonathan Ajo-Franklin<sup>5</sup>, Lianjie Huang<sup>6</sup>, Ghanashyam Neupane<sup>7</sup>, Roland Horne<sup>8</sup>, Yuran Zhang<sup>8</sup>, William Roggenthen<sup>9</sup>, Thomas Doe<sup>10</sup>, and the EGS Collab Team<sup>1</sup>**

**1 Lawrence Berkeley National Laboratory, Berkeley, California, USA**

**2 Sandia National Laboratories, Albuquerque, New Mexico, USA**

**3 Lawrence Livermore National Laboratory, Livermore, California, USA**

**4 Pacific Northwest National Laboratory, Richland, Washington, USA**

**5 Rice University, Houston, Texas, USA**

**6 Los Alamos National Laboratory, Los Alamos, New Mexico, USA**

**7 Idaho National Laboratory, Idaho Falls, Idaho, USA**

**8 Stanford University, Stanford, California, USA**

**9 South Dakota School of Mines and Technology, Rapid City, South Dakota, USA**

**10 TDoeGeo, Redmond, Washington, USA**

## **Keywords**

*EGS, EGS Collab, Stimulation, Simulation*

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<sup>1</sup> J. Ajo-Franklin, T. Baumgartner, K. Beckers, D. Blankenship, A. Bonneville, L. Boyd, S. Brown, J.A. Burghardt, C. Chai, T. Chen, Y. Chen, K. Condon, P.J. Cook, D. Crandall, P.F. Dobson, T. Doe, C.A. Doughty, D. Elsworth, J. Feldman, A. Foris, L.P. Frash, Z. Frone, P. Fu, K. Gao, A. Ghassemi, Y. Guglielmi, B. Haimson, A. Hawkins, J. Heise, M. Horn, R.N. Horne, J. Horner, M. Hu, H. Huang, L. Huang, K.J. Im, M. Ingraham, R.S. Jayne, T.C. Johnson, B. Johnston, S. Karra, K. Kim, D.K. King, T. Kneafsey, H. Knox, J. Knox, D. Kumar, K. Kutun, M. Lee, D. Li, J. Li, K. Li, Z. Li, M. Maceira, P. Mackey, N. Makedonska, C.J. Marone, E. Mattson, M.W. McClure, J. McLennan, T. McLing, C. Medler, R.J. Mellors, E. Metcalfe, J. Miskimins, J. Moore, J.P. Morris, S. Nakagawa, G. Neupane, G. Newman, A. Nieto, C.M. Oldenburg, T. Paronish, R. Pawar, P. Petrov, B. Pietzyk, R. Podgorney, Y. Polsky, J. Pope, S. Porse, B.Q. Roberts, M. Robertson, W. Roggenthen, J. Rutqvist, D. Rynders, M. Schoenball, P. Schwering, V. Sesetty, A. Singh, M.M. Smith, H. Sone, F.A. Soom, D.P. Sprinkle, S. Sprinkle, C.E. Strickland, J. Su, D. Templeton, J.N. Thomle, C. Ulrich, N. Uzunlar, A. Vachaparampil, C.A. Valladao, W. Vandermeer, G. Vandine, D. Vardiman, V.R. Vermeul, H.F. Wang, J. Weers, N. Welch, M.D. White, P. Winterfeld, T. Wood, S. Workman, H. Wu, Y.S. Wu, E.C. Yildirim, Y. Zhang, Y.Q. Zhang, Q. Zhou, M.D. Zoback

## ABSTRACT

The primary objective of the EGS Collab Project sponsored by DOE is to increase the understanding needed to efficiently implement enhanced geothermal systems (EGS). The EGS Collab project is a collaborative research environment studying stimulation of crystalline rock at the 10-meter scale. High-quality characterization and monitoring data are collected during stimulation and flow tests to allow comparison to numerical coupled process models in an effort to build confidence in the codes and improve modeling techniques. The Experiment 1 test bed, located at the Sanford Underground Research Facility (SURF) in Lead, SD at a depth of approximately 1.5 km is being used to examine hydraulic fracturing. The testbed was characterized using numerous field-based geophysical and geologic techniques and laboratory testing, and a well-instrumented test bed was created to allow us to carefully monitor fracture stimulation events and flow tests. A number of hydraulic stimulation tests at several locations in one well were performed, creating new fractures that connect to existing fractures between the injection and production boreholes. Long-term ambient and chilled water injection tests have been performed as an analog to EGS, and system changes resulting from these water injections have been monitored using geophysical monitoring, flow, temperature, and pressure measurements, tracer tests, and microbiology. Here, we summarize the tests performed, issues identified including poroelastic and thermoelastic effects, Joule-Thomson effects, restarting effects, indications of flow channeling, and the scientific findings to date from Experiment 1. We are currently designing a second test bed aimed at investigating shear stimulation (Experiment 2).

### 1. Introduction

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as an energy resource supporting the energy security of the United States. Estimates for EGS far surpass the resource base hosted by conventional hydrothermal systems, exceeding 500 GWe for the western US (Williams *et al.* 2008), and possibly an order of magnitude more (Augustine 2016) for the entire United States. Implementing EGS is attractive because of the magnitude of these resource estimates. There are technological challenges associated with developing EGS however, including: (1) the lack of a thorough understanding of techniques to effectively stimulate fractures in different rock types and under different stress conditions to communicate properly among multiple wells, (2) inability of techniques to image/monitor permeability enhancement and evolution at the reservoir scale at the resolution of individual fractures, (3) limited technologies for effective zonal isolation for multistage stimulations under elevated temperatures, (4) lack of technologies to isolate zones for controlling fast flow paths and control early thermal breakthrough, and (5) lack of scientifically-based long-term EGS reservoir sustainability and management techniques.

To facilitate the success of FORGE (Frontier Observatory for Research in Geothermal Energy, <https://www.energy.gov/eere/forge/forge-home>) and EGS, the DOE Geothermal Technologies Office (GTO) initiated the EGS Collab project. The EGS Collab project is utilizing readily accessible underground facilities to refine our understanding of rock mass response to stimulation. Our 10-m scale experiments under relevant stress conditions support validation of

thermal-hydrological-mechanical-chemical (THMC) modeling approaches. In addition, we are testing and improving conventional and novel field monitoring tools.

The EGS Collab project focuses on understanding and predicting permeability enhancement and evolution in crystalline rock, including how to create sustained and distributed permeability for heat extraction from the reservoir by generating new fractures that complement existing fractures. The EGS Collab project is a collaborative multi-national-lab, university, and commercial research endeavor bringing together a team of skilled and experienced subsurface process modeling, monitoring, and experimentation researchers and engineers to focus on intermediate-scale EGS reservoir creation processes and related model validation in crystalline rock (Kneafsey *et al.* 2018).

The project has planned three multi-test experiments to increase understanding of 1) hydraulic fracturing (Experiment 1- complete at the time of this writing), 2) shear stimulation (hydraulically opening properly oriented existing fractures allowing resulting stresses to move rock faces relative to each other such that they do not mate when the hydraulic pressure is removed - Experiment 2 – site characterization and design 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 tools and approaches. By doing this, we gain confidence in and improve the array of modeling tools in use. In Experiment 1, we have implemented a suite of rock/reservoir characterization methods potentially useful for EGS systems, as well as other methods available to improve understanding, and performed several highly monitored hydraulic fracture stimulations and flow tests (Knox *et al.* 2017, Morris *et al.* 2018, Fu *et al.* 2019). These include a range of geophysical and hydraulic measurements such as microseismic monitoring (MEQ), continuous active-source seismic monitoring (CASSM), electrical resistance tomography (ERT), and step-pressure and tracer tests (Ingraham *et al.* 2019, Johnson *et al.* 2019, Schoenball *et al.* 2019, Chi *et al.* 2020, Neupane *et al.* 2020). These help define the effective heat transfer surface area and determine the flow rate limitations for sustaining production well temperatures (Doe *et al.* 2014, Zhou *et al.* 2018). We are also developing new monitoring methods that are currently unable to work under geothermal reservoir conditions. One key component of the project is thermal circulation experiments that are being used to validate predictions based on field data and stimulations.

## 2. Site Description

Experiment 1 was performed on the 4850 (feet deep, ~ 1.5 km) level at the Sanford Underground Research Facility (SURF, Figure 1) in Lead, South Dakota (Heise 2015). Following an evaluation of a number of potential sites, this site was selected as most suitable to effectively meet the needs of the first experiment (Dobson *et al.* 2017). SURF, operated by the South Dakota Science and Technology Authority, is located in the former Homestake gold mine and hosts a number of world-class physics experiments related to neutrinos and dark matter, as well as to geoscience research (Heise 2015). As a former gold mine and current underground laboratory, SURF has been reasonably well characterized (Hart *et al.* 2014), and provides infrastructure (e.g., ventilation, power, water, and internet) and excellent staff dedicated to scientific research support, in addition to access to deep crystalline rock allowing cost-effective proximal

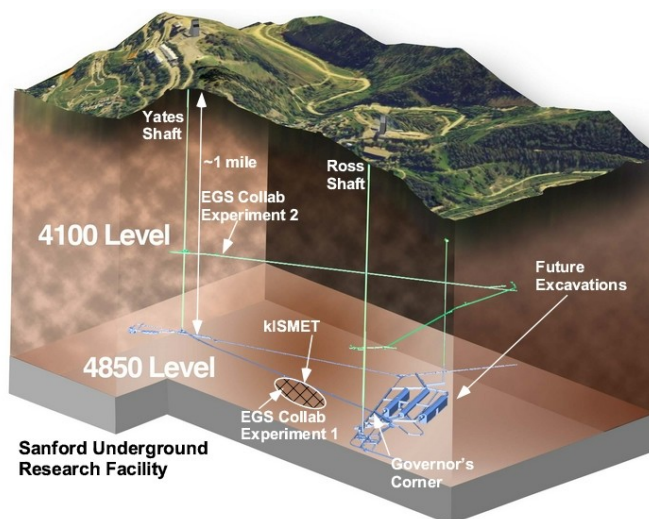
monitoring before, during, and after stimulation through multiple boreholes drilled from an underground tunnel. This addresses one of our priorities - performing tests under realistic in-situ stress conditions (Dobson *et al.* 2017). The maximum rock temperature at the 4850 level is about 35°C, which is not optimal for a geothermal project. However, achieving realistic temperatures *and* stress would involve costly deep drilling and would not facilitate detailed characterization and monitoring, thus preventing us from achieving the EGS Collab objectives.

### 3. Experiment 1

Experiment 1 was intended to investigate hydraulic fracturing to establish a fracture network that connects an injection well and a production well (Morris *et al.* 2018). 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 in approximately the minimum principal stress direction based on prior characterizations in adjacent rock (Oldenburg *et al.* 2017) so that hydraulic fractures would be expected to propagate orthogonally to the injection well. Six monitoring wells (yellow lines in Figure 2) were also drilled. Optical and acoustic televiwers, full waveform sonic, electrical resistivity, natural gamma, and temperature/conductivity logs were used in borehole characterization. Following borehole characterization, monitoring instrumentation was grouted in the monitoring wells. The test block was further characterized using seismic tomography (compressional- and shear-) using grouted and mobile sources and sensors (Linneman *et al.* 2018, Morris *et al.* 2018, Schwering *et al.* 2018), ERT baseline and during flow (Johnson *et al.* 2019), and extended hydrologic characterization including tracer tests (Mattson *et al.* 2019, Neupane *et al.* 2020). The detailed site characterization together with the array of installed monitoring systems and inversion methods helps to constrain the coupled process models.

Monitoring methods used during testing include: 1) passive seismic monitoring (Huang *et al.* 2017, Chen *et al.* 2018, Newman and Petrov 2018, Schoenball *et al.* 2019, Schoenball *et al.* 2020); 2) CASSM (Daley *et al.* 2007, Ajo-Franklin *et al.* 2011, Gao *et al.* 2018, Chi *et al.* 2020); 3) ERT in conjunction with dynamic electrical imaging using high contrast fluids (Johnson *et al.* 2014, Wu *et al.* 2018, Johnson *et al.* 2019); 4) acoustic emissions (Zang *et al.* 2017); 5) distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), and strain (DSS) changes (Daley *et al.* 2013). During flow and stimulation tests fracture aperture strain monitoring was performed using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool (Guglielmi *et al.* 2013, Guglielmi *et al.* 2015), continuous monitoring of pressure and flow conditions in the injection and production boreholes, tracer tests (Zhou *et al.* 2018, Mattson *et al.* 2019, Neupane *et al.* 2020), and wavefield imaging and inversion (Knox *et al.* 2016, Huang *et al.* 2017, Gao *et al.* 2018, Newman and Petrov 2018, Chen *et al.* 2019, Gao *et al.* 2020). Geophysical monitoring equipment installed and grouted into the monitoring wells includes seismic sensors (hydrophones and accelerometers), seismic sources and receivers for CASSM, ERT electrodes, thermistors, and fiber for DTS, DAS, and DSS. Laboratory measurements on selected core samples from the site measure fundamental physical rock properties and processes needed constrain the coupled process models (Huang *et al.* 2017), complementing data available from kISMET (Oldenburg *et al.* 2017, Wang *et al.* 2017) and previous geotechnical studies at

SURF. Additional laboratory investigations have been undertaken to provide process understanding (Frash *et al.* 2018, Frash *et al.* 2018, Yildirim *et al.* 2018, Frash *et al.* 2019, Ye *et al.* 2019, Frash *et al.* 2020, Ye *et al.* 2020). With the exception of very large data sets, all data collected and analyzed are stored on a data storage collaboration space (EGS Collab Data Foundry site) in preparation for inclusion in DOE's Geothermal Data Repository (Weers and Huggins 2019, Weers *et al.* 2020).

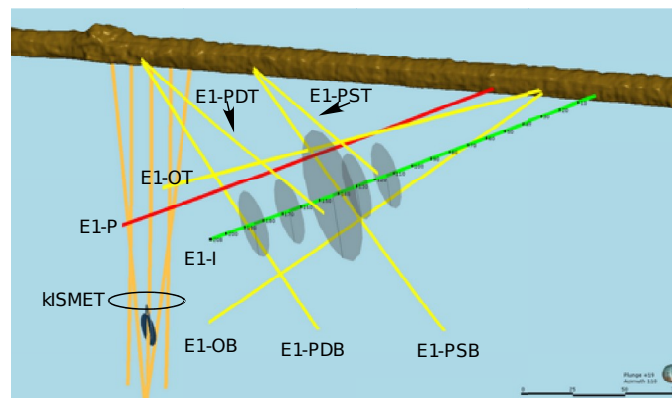


**Figure 1: Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, the location of the kISMET experiment, Experiment 1, and site investigated for Experiment 2. The site is located along the West Access Drift between the rhyolite dike swarms and Governor's Corner and adjacent to the kISMET site.**

In preparation for Experiment 1, over 450 meters of core was retrieved, logged, and photographed to identify foliation, veining, bedding, fractures, and variations in mineralogy. Experiment 1 boreholes are entirely within the Poorman Formation, a metasedimentary rock consisting of sericite-carbonate-quartz phyllite (the dominant rock type), biotite-quartz-carbonate phyllite, and graphitic quartz-sericite phyllite (Caddey *et al.* 1991). Carbonate minerals present consist of calcite, dolomite, and ankerite. The rock is highly deformed and contains carbonate, quartz veins/boudinage, pyrrhotite, and minor pyrite. Other mineral phases (in addition to those listed above) include graphite and chlorite. Permeability has been estimated to be from  $< 10$  nD to  $< 50$  to  $100$  nD (Frash *et al.* 2018, Ye *et al.* 2020). Optical and acoustic televiewer logs identified natural fractures crossing the boreholes and these were correlated with fractures mapped in the core samples and drift walls if possible. The adjacent kISMET boreholes (Figure 2) previously used for stress measurement were utilized to measure temperature gradients away from the drift walls. The ambient rock temperature at some distance into the rock is  $\sim 35^{\circ}\text{C}$ , and the drift temperature is  $\sim 20^{\circ}\text{C}$  from decades of ventilation. To the extent possible, all characterization data are integrated into the geologic framework model of the Experiment 1 site (Neupane *et al.* 2019). In coring the holes for kISMET, few fractures were encountered in 300 m of vertical core, so few were expected in Experiment 1. We encountered many fractures however, and cores, core images, and borehole logging have been used to begin to understand the natural fractures in our test bed (Roggenthen and Doe 2018, Ulrich *et al.* 2018, Neupane *et*

al. 2019). Selected core segments from the test bed were sent to the National Energy Technology Laboratory (NETL) for measurements of X-ray computed tomography, magnetic susceptibility, gamma density, compressional (P-) wave velocity, Ca/Si, Ca/Al, Si/Al, and Fe/S ratios, abundance of light elements, Ca, and Si. In addition, cores have been sent out to researchers at a number of institutions to examine rock properties and behavior, and native biota.

Stress measurements conducted adjacent to the Experiment 1 site as part of the kISMET project augment our site characterization (Oldenburg *et al.* 2017). Based on a re-evaluation of kISMET data, the fractures generated from these tests indicate that  $S_{\text{hmin}}$  is about 21.7 MPa (3146 psi) and trends approximately **\*\*N-S (azimuth of 2 degrees), with a slight plunge of 9.3 degrees to the NNW\*\***<sup>2</sup> (Kneafsey *et al.* 2020). The vertical stress magnitude is estimated to be ~41.8 MPa (6062 psi) for the depth of testing (~1530 m), and the horizontal maximum stress is estimated to be 34.0 MPa (4931 psi) (Dobson *et al.* 2018).



**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  $S_{\text{hmin}}$ , gray disks indicate nominal hydraulic fractures.

### 3.1 Stimulations Performed

An excellent summary of tests performed is presented in (White *et al.* 2019), short-term flow tests are summarized in (Kneafsey *et al.* 2019), and tracer tests are summarized in Mattson *et al.* (2019), Neupane *et al.* (2020). Four stimulation tests and short- and long-term ambient temperature and chilled water flow tests have been performed, resulting in many data sets and analyses (Chen *et al.* 2019, Frash *et al.* 2019, Fu *et al.* 2019, Huang *et al.* 2019, Johnson *et al.* 2019, Lu and Ghassemi 2019, Mattson *et al.* 2019, Pan *et al.* 2019, Schoenball *et al.* 2019, Templeton *et al.* 2019, Weers and Huggins 2019, White *et al.* 2019, Winterfeld *et al.* 2019, Wu *et al.* 2019, Wu *et al.* 2019, Ye *et al.* 2019, Fu *et al.* 2020, Wu *et al.* 2020).

<sup>2</sup> **\*\*corrected\*\*** from Wang *et al.* 2017, Ulrich *et al.* 2018

Briefly, notches were scribed at locations along the injection well to encourage fracture initiation perpendicular to the well, and the first stimulation attempt was performed at the 142' Notch (142 feet from the collar of E1-I) (Morris *et al.* 2018, White *et al.* 2018). The packer interval (approximately 1.65 m [65 inches] including the SIMFIP tool) encompassed a large apparently healed natural fracture. The stimulation was planned to occur in 3 steps. The initial stimulation was designed such that it might create an ideal 1.5 m radius penny-shaped fracture prior to being shut in for the night. The second step would extend the fracture to 5 m radius followed by shutting in for the night, and the third step would extend the fracture to the production borehole approximately 10 m away. The injection volume required to attain the planned fracture extents (1.5 m, 5 m) was computed assuming ideal conditions considering both toughness and viscosity-dominated regimes (Morris *et al.* 2018). Unexpected results were encountered when pressurizing at this location including water flow returning up the injection borehole and a higher-than-expected fracture initiation pressure. Our analysis indicates that a hydraulic fracture was created with a breakdown pressure of 31 MPa (4500 psi), probably intersecting the observed natural fracture. A total of twelve liters of water were injected in this test. As shear stimulation was not intended in this test and the results indicated that we might be pumping into the natural fracture, the stimulation packer set was moved downhole to the 164' Notch.

The stimulation at the 164' Notch was carried out in steps over three days with shut-in periods between each step. In the first step, 2.1 L of water was injected at a stable rate of 200 mL/min. The propagation pressure was 25.43 MPa (3688 psi) and the instantaneous shut-in pressure (ISIP) was 25.37 MPa (3679 psi). In the second step, 23.5 L of water was injected at 400 mL/min resulting in slightly higher propagation pressure and ISIP (25.95 and 25.82 MPa respectively [3763 and 3744 psi]). The pressure decay following this step indicated that the hydraulic fracture may have intersected a natural fracture. The third step was performed at 5 L/min and had an injection volume of 80.6 L, resulting in a propagation pressure and ISIP of 26.88 and 25.31 MPa (3898 psi and 3670 psi), and water being produced at E1-P. In addition to intersecting E1-P, this stimulation intersected the E1-OT monitoring well (located between the injection and production boreholes), as indicated by seismic sensors, a temperature increase measured by the DTS, and eventually water leaking out the top of the grouted E1-OT well. This intersection and leakage from this well were problematic and required remediation including epoxy grouting and application of a custom well cap with wire feedthroughs that was backfilled with epoxy.

The third stimulation was conducted at the 128' Notch, attempting to avoid a fracture that connects wells E1-OT and E1-P (the "OT-P connector") while still connecting the injection and production wells. In this test, flow bypassed the top injection packer through fractures, and resulted in a hydraulic fracture connecting to E1-OT, but not E1-P.

After this stimulation, a medium-term set of hydraulic characterization tests was conducted at the 164' Notch. Following that, a second stimulation experiment was completed at the 142' Notch by carefully placing the packer over regions of concern. This hydraulic stimulation experiment involved high flow rates and pressures, and extended at least one hydraulic fracture to E1-OB and E1-P, and also connected to all other wells except for E1-PDB according to DTS evidence. For stimulations at both the 164' and 142' Notches, micro-seismic event locations (Schoenball *et al.* 2019) consistently indicated that the fracture extended toward the drift. This was predicted by



earlier modeling (Fu *et al.* 2018, White *et al.* 2018) of fracture growth under the stress gradient created by thermal cooling of the rock by the drift.

### 3.2 Flow Tests

Long-term ambient temperature and chilled water flow tests were performed for about 11 months. In these tests, water was introduced at the 164' Notch interval, typically at 0.4 L/m. This rate, although lower than desired, did not result in additional microseismicity, indicating that the stimulated system was stable. During the first part of the flow test, ambient temperature "mine" water was injected into the system. On May 8, 2019, chilled mine water injection was initiated. Volumetric recovery of the injected water increased over the duration of the test ranging from about 70% to about 95%. There are some uncertainties in these data because not all water was recovered through the wells. Some water was collected off wet patches on the drift wall, requiring estimation of these quantities.

Nearly 100 channels of operational and test data were collected during flow tests. A small portion of these data are shown in Figure 3. Panels 1 and 2 show the flow rate of the injected water and the injected water pressure, with Panel 2 showing the pressure at enhanced resolution. Intermittent shutdowns occurred due to a number of factors. Panel 3 shows the volumetric collection of water at the major collection locations. It is interesting to note that the proportions of the water collected change over time, and sometimes these changes are not related to applied stimuli (flow, temperature, or outflow control change). In the production well, there are two primary collection locations, called the production interval (between the straddle packers – E1-PI) where flow enters through natural fractures, and the region below the bottom packer (E1-PB) where flow enters the well through hydraulic fractures. Panel 4 shows temperatures at a number of locations including in the injection interval, E1-PI and E1-PB. The accuracy of some of these temperature measurements is not entirely reliable due to damage to thermistors (discussed below). For injecting chilled water, the injection water line is contained within a chilled line (tube-in-tube heat exchanger) and the temperatures of the water flowing outside the injection tube at the inlet and outlet are also shown. Panel 5 shows a subset of the data shown in Panel 4 at higher resolution.

A number of features in the data are worth discussing, indicated by letters A-G. First, note that an injection pressure significantly higher than the ISIP (on the order of 34.5 MPa (5,000 psi) vs. 25.5 MPa (3700 psi)), is required to maintain the selected flow rate, and this pressure always rises under continuous flow conditions. For example, "A" in Panels 1 and 2 in Figure 3 shows the behavior of the system with respect to a brief injection shut down. Prior to the shutdown, the injection pressure had slowly increased under constant flow. The shutdown occurred resulting in a drop in the injection interval pressure. Upon restarting soon afterwards, a lower pressure was required to inject water at the same flowrate. This pressure increased over time until another shutdown or stimulus occurred. Several explanations have been offered for this behavior: biological effects, chemical effects, and poroelastic effects. Our data show that in all cases, the fracture is propped by the injection pressure (hydropropped), thus there is very little flow until the injection pressure is sufficient to open the aperture. In the biological effects explanation, growing microbes coat the fractures (biofilm) and reduce the available aperture available for flow. When the pressure is reduced and the fracture closes, the biofilm is compacted, opening the

aperture when flow resumes. As the microbial biofilm thickens during flow the permeability decreases and increased pressure is required to maintain flow. The chemical explanation is similar, in that oxygen or other reagent in the injected mine water causes dissolution and precipitation reactions resulting in the buildup of mineral precipitates on the fracture faces reducing the fracture aperture. When pressure declines and the aperture closes, the precipitate is compacted, and upon repressurization the aperture is opened but then is slowly occluded by the buildup of more precipitate, requiring added pressure to maintain flow. The third and probably most likely explanation is poroelasticity. The porespace in the rock contains fluid that is initially pressurized to a lower value than the flow pressure (hydrostatic pressure could be as high as ~ 14.5 MPa). When the fracture is pressurized and opened, the rock and pore fluids are compressed by the higher-pressure water. As the pressure from the injected water diffuses into the rock, the rock and pore space relax back towards their initial spatial configuration causing the aperture to close some. Upon shutdown and depressurization, the reverse occurs and the pressure diffuses from the rock to the aperture. Upon repressurization, the fracture is again opened and rock and pore fluids are compressed and the process continues. These processes do not need to occur over the entire fracture surface to cause the observed effects, and only need to occur at “pinch point” locations.

Each of these explanations has strengths and weaknesses. We know there are microbes in the system (Zhang *et al.* 2019), but have not quantified their growth rate under injection conditions. We have also injected biocide, yet still witnessed the pressure increase. We know that chemical reactions occur as well, as our production packer is covered by dark precipitates. X-ray diffraction analyses of several samples has revealed the presence of goethite, calcite, ettringite, Fe-chlorite, and gypsum. The repeatable rate of pressure increase is difficult to explain using chemistry, because the rate of chemistry before and after the shutdown would be expected to be similar, and the same can be said for biofouling. Numerical models have been able to show the pressure trend resulting using the poroelastic explanation, however some biofouling and precipitate fouling are likely to also be occurring simultaneously.

The pump was stopped briefly when chilled water (~ 11 to 12°C) was introduced into the system (see “B” in Panels 2 and 4 of Figure 3). The expected drop in injection pressure occurred, but instead of the injection pressure immediately climbing as described above, the injection pressure dropped for some time before climbing again (see “B” in Panel 2). This can be explained by a thermoelastic effect. The chilled water caused the rock to contract, opening the fractures and increasing the permeability. This would occur near the borehole, however farther from the borehole where the injected water had warmed, the chemical, biofouling, and poroelastic effect are likely explanations for the pressure increase. The reverse effect is shown at “C” in Panels 2 and 4 of Figure 3. When the chiller was shut off, the injected water was warmer. The injection pressure increased as the near-borehole fracture apertures were likely reduced by expanding rock. When the chillers were reengaged, the injection pressure declined again in response to chilling the near-borehole rock. Similar behavior is repeated (“D”).

Pump problems caused a shutdown (“E” in Panels 1, 3, and 4 in Figure 3), allowing the system to relax for several days. This shutdown induced a temperature transient in the injection interval,

in addition to collection flowrate transients from the collection locations. The system returned to normal behavior after several days of pumping.

Temperatures in the production well (see “F” in Panels 4 and 5 in Figure 3) were difficult to explain. The temperatures of water flowing through the rock collected from nearby locations started to become significantly different and differ from expectations. A number of explanations were proposed, but the most likely one was that the temperature measurements were flawed. The temperatures are measured using thermistors cased in stainless steel tubes, and initially these thermistors were electrically isolated from the rest of the system. Resistance checks indicated that there was some conductivity where there should not be any. Deconstruction of the thermistors showed swollen epoxy seals and water on the thermistor leads, causing an electrical connection between the thermistor leads and the packer. The thermistors were redesigned, remanufactured, recalibrated, and reinstalled. In spite of the errors in temperature measurements, the failed thermistors may still provide a relative indication of changes over short durations.

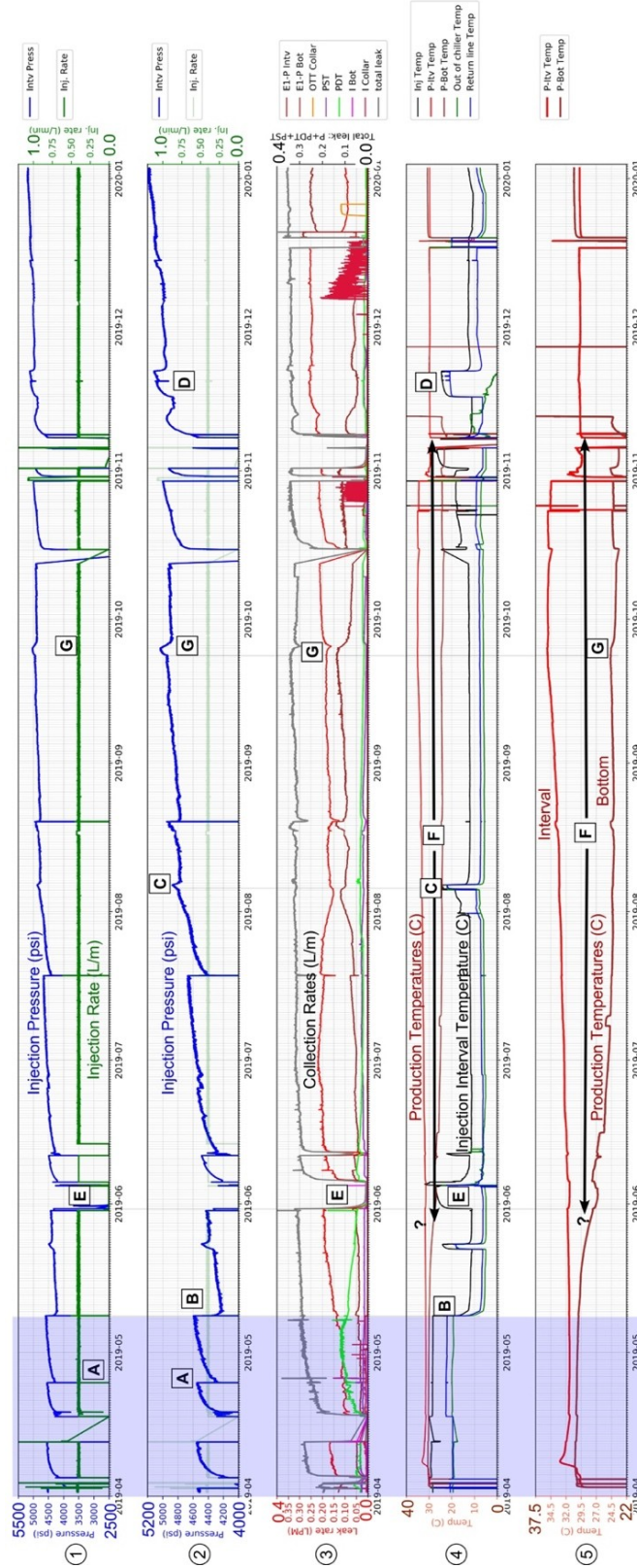


Figure 3. Data summary from long-term flow tests at the 164' Notch. Panels 1 and 2 show the injection pressure and injection rate; Panel 3 shows the out-flow rates from different wells and two isolated

segments in well E1-P; Panel 4 shows the injection interval, production interval, and bottomhole fluid temperatures and other temperatures, and Panel 5 shows the same temperatures over the range of 22°C to 37.5°C. The blue shaded region indicates the ambient temperature flow test, whereas chilled water is injected over the rest of the test.

“G” in Panels 1, 2, 3, and 5 in Figure 3 show an event that occurred during flow. Without applying a change to the system (no flow or temperature change was applied), the resistance to flow increased, and then decreased. This resulted in changes in flow paths indicated by significant flowrate changes in the collection rate from the production interval and the bottom of the production hole, and a step change in leakage from monitoring well PST. A slight change in produced water conductivity was observed at the same time, along with a change in temperature (if the relative change can be accepted as real) in the production hole bottom temperature. This provides an example of the dynamic nature of the system. Cross correlation of data sets may shed more light on this.

### 3.3 Inferences from System Microbial Analyses

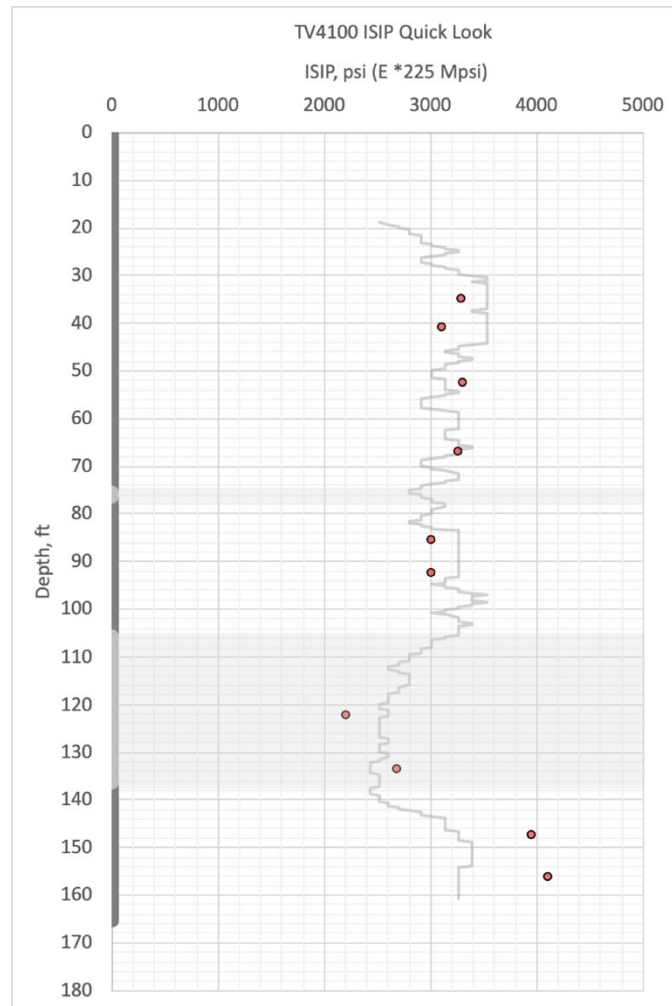
Formation fluids produced at or near the site were sampled during the drilling phase. Besides routine geochemistry measurements, the samples were additionally subjected to high-throughput DNA sequencing analyzing the entire microbial community population therein (Zhang *et al.* 2019). Despite the typically substantial heterogeneity across microbial community profiles of fluids spatially distributed throughout the site, OT and PST were found to host microbial communities highly similar to each other, suggesting natural hydraulic communication. The natural connectivity was also corroborated by the core-log open fractures in respective wells that conform to the same planar structure. Our DNA findings suggest that the microbial population indigenous to reservoir fluids can serve as valuable natural "tracers" revealing where the fluids come from with high specificity. Such information is accessible without the need of sensor deployment or establishment of interwell flow tests.

## 4. Experiment 2

A testbed for Experiment 2 to examine shear stimulation is being characterized and designed for implementation on the 4100 level at SURF (about 1.25 km deep) in the Yates amphibolite formation. In this experiment, the goal is to stimulate the rock via shear stimulation. We have begun characterization of the potential testbed, including drilling and coring one 50 m vertical borehole, and one 10 m subhorizontal hole. The vertical borehole identified and penetrated a thick (~11 m) rhyolite layer. This layer has a significantly different stress regime than either the upper and lower amphibolite. Ten “minifrac” stress tests have been performed in the vertical borehole (Figure 4), and the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool was used to identify displacement across the interval upon stimulation at eight locations, some collocated with “minifrac” stress tests (Figure 5). Instantaneous Shut-In Pressures (ISIP) providing minimum principal stress information can be grouped into 3 categories. ISIP values of the amphibolite below the rhyolite are around 27.6 MPa (4000 psi), while the ISIP in the rhyolite are around 18.6 MPa (2700 psi) and in the upper amphibolite around 21.4 MPa (3100 psi). The test bed for Experiment 2 is designed to be entirely above the rhyolite layer, trying to avoid this heterogeneity. 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. Drilling and coring for building this test bed is expected in 2020.

Figure 5 shows measurements made using the SIMFIP tool on the location of the minifrac test below the rhyolite where the pressure required to open the fracture and flow was 27.5 MPa (3990 psi). Upon pressurization, the fracture began to open primarily vertically, then horizontally to the east when the zone was shut in. During shut-in, most of the vertical displacement was recovered, but not the horizontal displacement. The pressure step-downs resulted in displacement towards the west and north, and at the removal of the pressure a displacement of about 75 microns to the northwest remained.



**Figure 4.** Instantaneous shut-in pressures for tests at 10 locations in the 50 m vertical borehole on the 4100 level. 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.

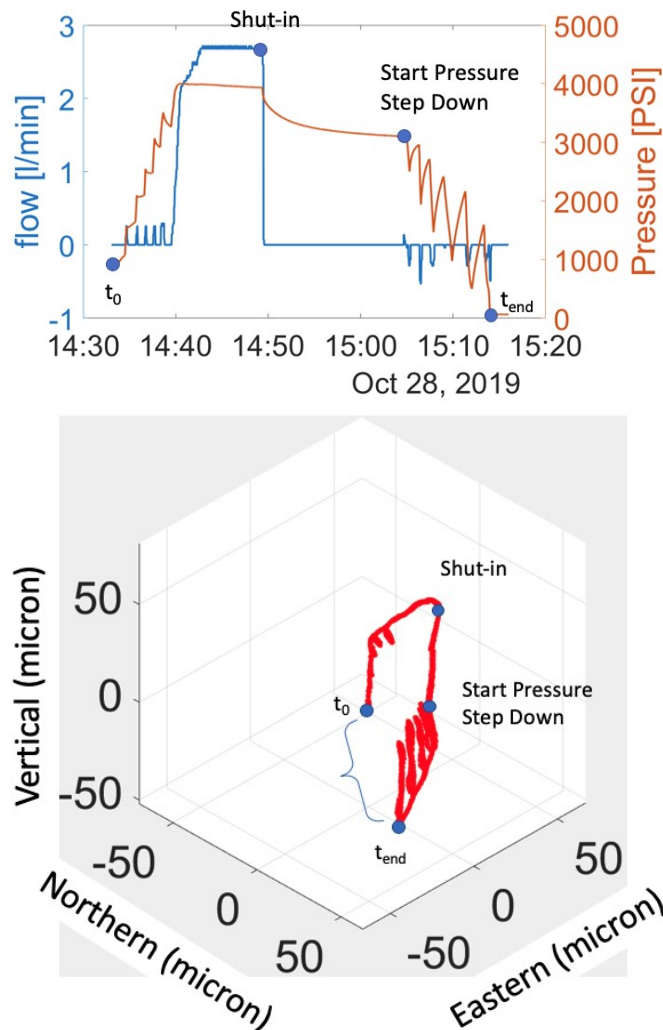
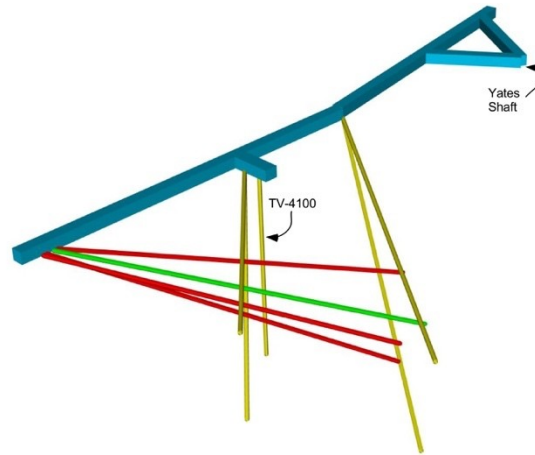


Figure 5. Results of SIMFIP test in a previously stress tested zone in the vertical borehole on the 4100 level. Top – Injection flow and pressure. Bottom – Displacements in 3-D indicated by the SIMFIP tool.

A schematic of the expected borehole layout for Experiment 2 is shown in Figure 6. 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. We plan to put two fans of monitoring wells oriented approximately orthogonally to the injection and production wells to deploy our monitoring sensors. 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.



**Figure 6. Expected well orientations for Experiment 2. 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.**

## 4. Scientific Findings

### 4.1 Poroelasticity

Poroelasticity likely plays an important role in the response of the rock-fracture system to fluid circulation. Poroelasticity may dominate the evolution of the permeability of the hydraulically propped fractures. This effect might be expected at FORGE and in EGS systems, and should be further studied.

### 4.2 Thermoelasticity

Two significant thermoelastic effects were observed: 1) cooling of the rock mass from the from ventilation over decades and 2) from the injection of cool water into the warm fractured rock. In general, fracture growth from stimulations on the 4850-level tended to proceed in the direction predicted (towards the drift), providing an element of validation of the thermoelastic effect. Injection of chilled water during the flow test initially resulted in an increase in permeability prior to the observation of what we have attributed to the poroelastic effect. This effect could be expected at FORGE and in EGS systems where cooler water will be introduced into hot rock.

### 4.3 Local geology

A number of local geology effects have been observed to affect stimulation and flow behavior. Nearby kISMET drilling showed few fractures, however EGS Collab drilling identified many fractures, particularly in the upper regions of the test bed. Electrical resistance tomography data concurred with the core data that the geology was more complicated than originally assumed based on earlier observations (Johnson *et al.* 2019). Tomography/full-waveform inversion of campaign seismic data revealed that the host rock can be represented by a horizontal transverse isotropic (HTI) medium (Gao *et al.* 2020). Comparisons of stress measurements from kISMET and from a vertical borehole on the 4100 level also highlight effects of local geology, particularly



the presence of an unexpected rhyolite body on the 4100 level having a lower minimum principal stress separating the higher minimum principal stress amphibolite beneath the rhyolite from a medium value minimum principal stress amphibolite above the rhyolite. More detailed and a higher number of methods of characterization will aid in understanding the local geology.

The role of natural fractures can be estimated a-priori if enough information including stress, fracture orientations, and interconnectedness can be determined by characterization. Discrete fracture network models graphically summarize this information, making interpretation of stimulation behavior more tractable.

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, Kneafsey *et al.* 2019, Chi *et al.* 2020). The SIMFIP tool was also used to quantify rock motion across a fracture or fractured zone (Kneafsey *et al.* 2019) in a borehole during stimulation, and in a number of stimulations in a vertical borehole on the 4100 level. These quantifications provide key insights into stimulation.

It is still not clear whether or how well heat transfer area can be predicted using chemical tracer tests. This comparison is extremely important for EGS.

The intersection of a stimulated fracture with a borehole containing a DTS fiber indicated temperatures measured were higher than expected from heat convection and conduction. This increased temperature may be explained by the Joule-Thomson effect with the sudden decrease in water pressure upon entering the well (Zhang *et al.* 2018). The known location of the fracture intersection the monitoring well indicated by the DTS provided a validation point for the inversion of microseismic monitoring data, indicating that the inversions provided accurate event locations.

## 5. Concluding Remarks

A number of stimulations and flow tests have been performed for the EGS Collab Experiment 1. Our stimulations were successful in connecting not only our injection and production wells, but also connected a natural fracture network, and fast flow pathways in monitoring wells. The volume fraction of injection water that is recovered has increased over the duration of the flow test to nearly 100%. Chilled water was injected for about 10 months, but decreases in the outlet temperature were not observed. This is consistent with early predictions (Zhang *et al.* 2018, Zhang *et al.* 2018, Zhang *et al.* 2018, Winterfeld *et al.* 2019, Wu *et al.* 2020). Flow tests have shown clear thermoelastic effects, indicated by a lowering of the injection pressure at constant flow for the initial injection of chilled water, or an increased injection pressure with ambient temperature water. Poroelastic effects are also strongly indicated by the data, as the injection pressure required to maintain constant inlet flow in our hydraulically propped fractures increases fairly continuously over time. Understanding local geology including stress magnitude and orientation; and natural fracture abundance and orientation is critical in performing suitable stimulations.

Design of Experiment 2 is well under way, and we are anxiously awaiting addressing the challenges a new test bed and new stimulation goals will bring. We will be attempting to

hydroshear fractures in the stimulations and to investigate flow in these fractures. We anticipate starting drilling in 2020, and hope to apply our lessons learned to gain better understandings informing EGS.

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