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The EGS Collab Project: Learnings from Experiment 1

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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). One goal of the EGS Collab project is to create a collaborative research environment in which to study stimulation of crystalline rock at the 10 meter scale. Key to this effort is the collection of high quality data during stimulation and flow tests to allow comparison to numerical coupled process models in an effort to build confidence in the codes and modeling techniques used. In response to this research need, the EGS Collab team has 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 (Experiment 1). We are currently designing a second test bed aimed at investigating shear stimulation (Experiment 2).

At the Experiment 1 location, we have characterized our host rock using laboratory testing and numerous field-based geophysical and geologic techniques, and created a well-instrumented test bed to allow us to carefully monitor fracture stimulation events and flow tests. In addition to the installed geophysical sensors, we have used tracer tests, differences in the ambient microbial communities at flow

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collection locations, and cold-water injection to inform us about dynamic flow pathways. In Experiment 1, we have hydraulically stimulated the host rock a number times at several locations in one well, creating new fractures that connect to existing fractures between the injection and production boreholes. We have performed long-term ambient and chilled water injection tests as an analog to EGS, and have monitored system changes resulting from these water injections through geophysical monitoring, flow 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 primary learnings to date from Experiment 1.

1. INTRODUCTION

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as an energy resource supporting the energy security of the United States with estimates exceeding 500 GWe for the western US surpassing the resource base hosted by conventional hydrothermal systems [*Williams et al.*, 2008], to an order of magnitude more [*Augustine*, 2016] for the entire United States. Because of the magnitude of these resource estimates EGS is attractive to utilize. Technological challenges associated with developing EGS include: (1) the lack of a thorough understanding of techniques to effectively stimulate fractures in different rock types and under different stress conditions to communicate 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 intermediate scale (on the order of 10 m) experiments under relevant stress 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- under way at the time of this writing), 2) shear stimulation (Experiment 2 - 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 can gain confidence in and improve the array of modeling tools in use. To date in Experiment 1, we have performed several highly monitored hydraulic fracture stimulations and flow tests, and implemented a suite of rock/reservoir characterization methods potentially useful for EGS systems, as well as other methods available to improve understanding [*Knox et al.*, 2017; *Morris et al.*, 2018]. These include a range of geophysical and hydraulic measurements such as microseismic monitoring (MEQ), continuous active-source seismic monitoring (CASSM), electrical resistance tomography, and step-pressure and tracer tests. 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 will be used to validate predictions based on field data and stimulations.

2. EGS COLLAB EXPERIMENT 1

Site Description

Experiment 1 is being performed on the 4850 (feet deep) 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. It 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 (e.g., 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 cost-effective proximal monitoring of a deep crystalline rock mass 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.

Experiment 1 was intended to establish a fracture network that connects an injection well and a production well using hydraulic fracturing [*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 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 tend to propagate orthogonally to the injection well. 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 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], electrical resistance tomography (ERT) for baseline and during flow [*Johnson et al.*, 2019], and extended hydrologic characterization including tracer tests [*Mattson et al.*, 2019b]. The detailed site characterization together with the array of installed monitoring systems and inversion methods helps to constrain the coupled process models. These methods include: 1) passive seismic monitoring [*Chen et al.*, 2018; *Huang et al.*, 2017; *Newman and Petrov*, 2018; *Schoenball et al.*, 2019]; 2) CASSM [*Ajo-Franklin et al.*, 2011; *Daley et al.*, 2007; *Gao et al.*, 2018]; 3) ERT in conjunction with dynamic electrical imaging using high contrast fluids [*Johnson et al.*, 2014; *Johnson et al.*, 2019; *Wu et al.*, 2018]; 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 is performed using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool [*Guglielmi et al.*, 2015; *Guglielmi et al.*, 2013], continuous monitoring of pressure and flow conditions in the injection and production boreholes, tracer tests [*Zhou et al.*, 2018], and wavefield imaging and inversion [*Chen et al.*, 2019a; *Gao et al.*, 2018; *Huang et al.*, 2017; *Knox et al.*, 2016; *Newman et al.*, 2018]. Geophysical monitoring equipment installed and grouted into the monitoring wells includes seismic sensors (hydrophones and accelerometers), seismic sources and receivers for Continuous Active-Source Seismic Monitoring (CASSM) [*Ajo-Franklin et al.*, 2011; *Daley et al.*, 2007], ERT electrodes, thermistors, and fiber for distributed temperature, distributed strain, and distributed acoustic sensing. Laboratory measurements on selected core samples from the site measure fundamental physical rock properties 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. Additionally, laboratory investigations have been undertaken to provide additional process understanding [*Frash et al.*, 2018a; *Frash et al.*, 2018b; *Frash et al.*, 2019b; *Ye et al.*, 2019; *Yildirim et al.*, 2018]. 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 [*Weers and Huggins*, 2019].

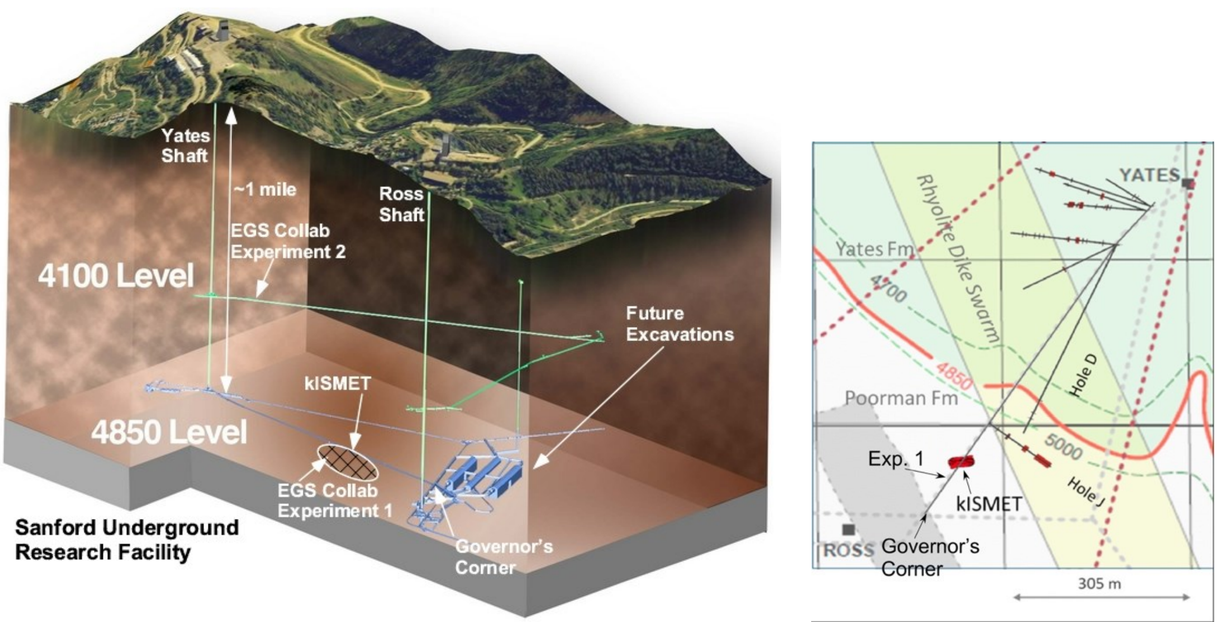

Figure 1: a) Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, the location of the kISMET experiment, and Experiment 1. b) Geologic map of the 4850 level of SURF in the vicinity of the site of Experiment 1. Both of these areas are located along the West Access Drift between the rhyolite dike swarms and Governor's Corner.

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. 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 previously used for stress measurement were utilized to measure temperature gradients away from the drift walls. To the extent possible, all characterization data are being integrated into the geologic framework model of the Experiment 1 site [*Neupane et al.*, 2019]. Few fractures were encountered in the 300 m of core collected from the adjacent near-vertical wells at the kISMET site, 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 [*Neupane et al.*, 2019; *Roggenthen and Doe*, 2018; *Ulrich et al.*, 2018]. 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_{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**[2]. 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].

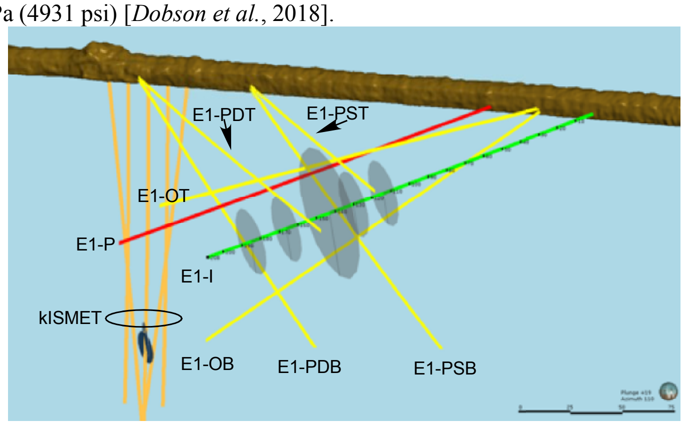

Figure 2: Schematic of wells for Experiment 1 along the West Drift on the 4850 level of SURF. The green line represents the stimulation (Injection) well (E1-I), the red line represents the Production well (E1-P), yellow lines represent monitoring wells, and orange lines represent kISMET wells. The two 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_{hmin} and the gray disks indicate nominal hydraulic fractures.

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.*, 2019a]. 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.*, 2019b; *Frash et al.*, 2019a; *Fu et al.*, 2019; *Huang et al.*, 2019; *Johnson et al.*, 2019; *Lu and Ghassemi*, 2019; *Mattson et al.*, 2019b; *Pan et al.*, 2019; *Schoenball et al.*, 2019; *Templeton et al.*, 2019; *Weers et al.*, 2019; *White et al.*, 2019; *Winterfeld et al.*, 2019; *Wu et al.*, 2019a; *Wu et al.*, 2019b; *Ye et al.*, 2019]. Briefly, notches were scribed at locations along the injection well to encourage perpendicular fracturing and the first stimulation attempt was performed at the 142' Notch (142 feet from the collar of E1-I). The packer interval (approximately 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 being shut in for the night, and the third step would extend the fracture to the production borehole approximately 10 m away. Pressurizing at this location led to unexpected results including water flow returning up the 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 5L/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.

[2] **corrected** from *Ulrich et al.* [2018]; *Wang et al.* [2017]

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 ft and 142 ft notches, micro-seismic event locations [*Schoenball et al.*, 2019] consistently indicate that the fracture extended toward the drift (Figure 3). 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.

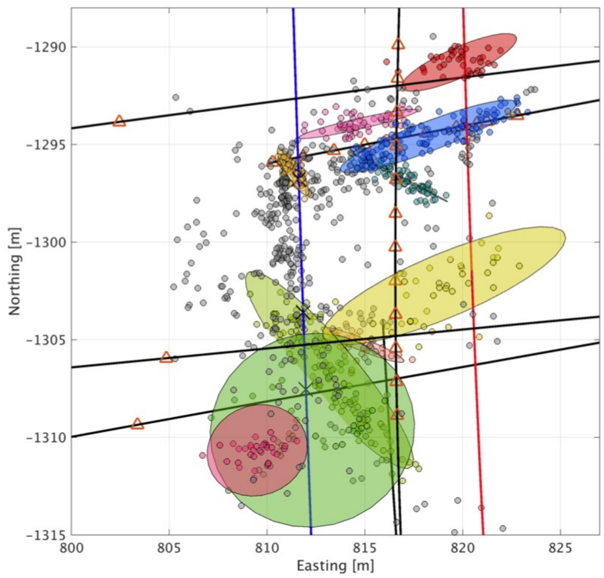

Figure 3: Fracture planes identified from MEQ locations.

Flow Tests

Long-term ambient temperature and chilled water flow tests have been underway for about 10 months. In these tests, water is introduced at the 164' Notch interval, typically at 0.4 L/m. This rate, although lower than desired, does not result in additional microseismicity, indicating that the stimulated system is 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 (Figure 4) reaching near full recovery. 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. In spite of reaching high volumetric recovery, tracer and microbial analyses may indicate that the recovered water is different from the injected water, indicating perhaps that the injected water is displacing native water in the system, or the water is altered in different ways along different flow paths.

A portion of the nearly 100 channels of operational and test data collected highlighting flow test data are shown in Figure 5. Panels 1 and 2 show the flow rate of the injected water and the injected water pressure, with Panel 2 showing the pressure at different scale to enhance resolution. Although the flow tests have been in progress for about 10 months, there have been intermittent shutdowns 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). The primary collection locations are two zones in the production well, 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. Note the accuracy of some of these temperature measurements is being investigated after damage to thermistors was discovered (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. Panel 6 shows the electrical conductivity of the injected water (steady) and the water from E1-PI, and the difference in temperature (varying) between the inlet and outlet on the tube-in-tube heat exchanger indicating the amount of chilling occurring.

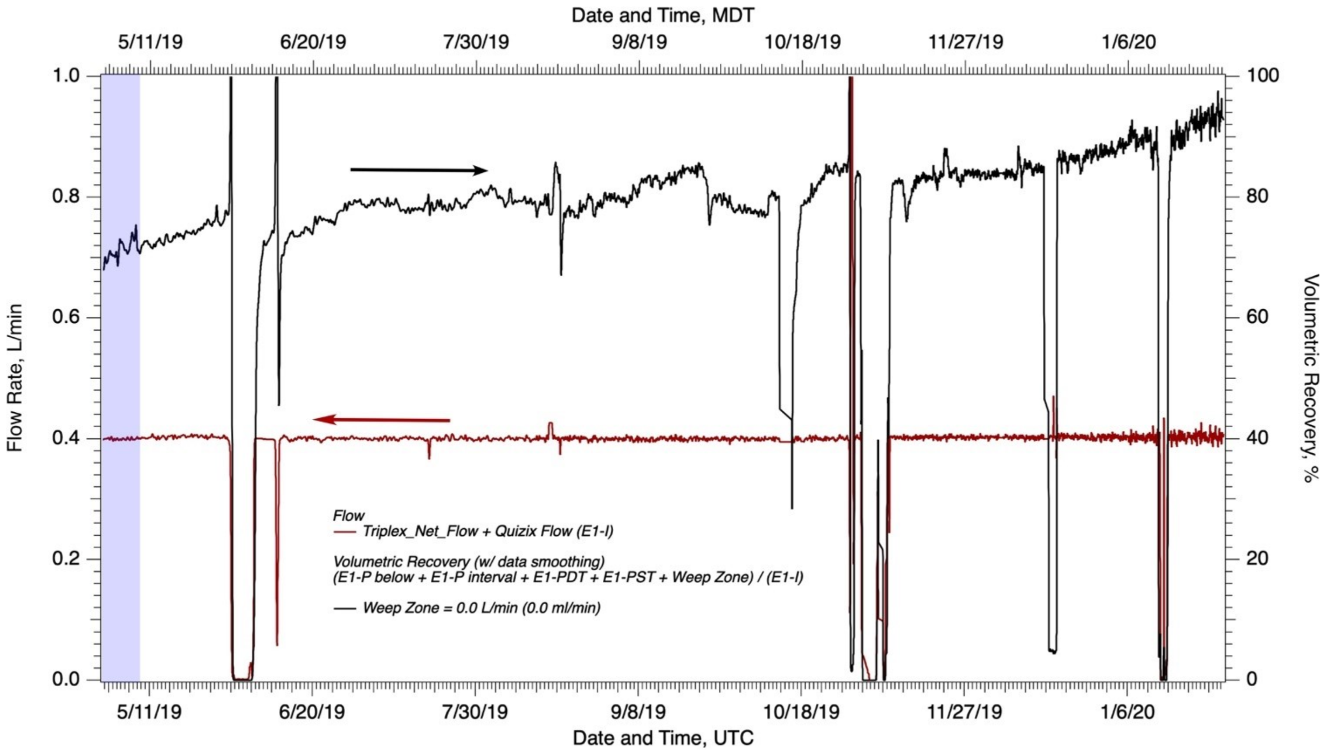

Figure 4. Volumetric fluid recovery and relative recovery.

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 25.5 MPa (3700 psi) vs. ~ 34.5 MPa (5,000 psi)), is required to maintain the selected flow rate, and this pressure always continues to rise under continuous flow conditions. An example identified by “A” in Panels 1 and 2 in Figure 5 shows the behavior of the system with respect to a brief shut down of injection. Prior to the shutdown, the injection pressure slowly increases under constant flow. The shutdown occurs resulting in a drop in the injection pressure. Upon restarting soon afterwards, the pressure increases, but a lower pressure is required to inject water at the same flowrate. This pressure increases over time until another shutdown or stimulus is applied. Several explanations have been offered for this behavior, biological, chemical, and poroelastic. In all cases, the fracture is propped by the injection pressure, thus there is very little flow until the injection pressure opens the aperture. In the first explanation, growing microbes lining the fractures (biofilm) reduce the available aperture available for flow. When the pressure is reduced, the biofilm is compressed, 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 in the injected mine water causes dissolution and precipitation reactions resulting in the buildup of mineral precipitates on the fracture faces reducing the aperture. When pressure declines, the precipitates are compressed, and upon repressurization the aperture is again slowly occluded by the buildup of precipitates 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. When the fracture is pressurized and opened, the rock and pore fluids are compressed. As the pressure from the injected water diffuses into the rock, the rock and porespace relax back towards their initial spatial configuration causing the aperture to reduce. Upon shut down 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 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 points”. 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. In spite of the precipitate color, the predominant mineral is calcite. The somewhat 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 applying the poroelastic explanation, however some biofouling and precipitate fouling may be occurring simultaneously.

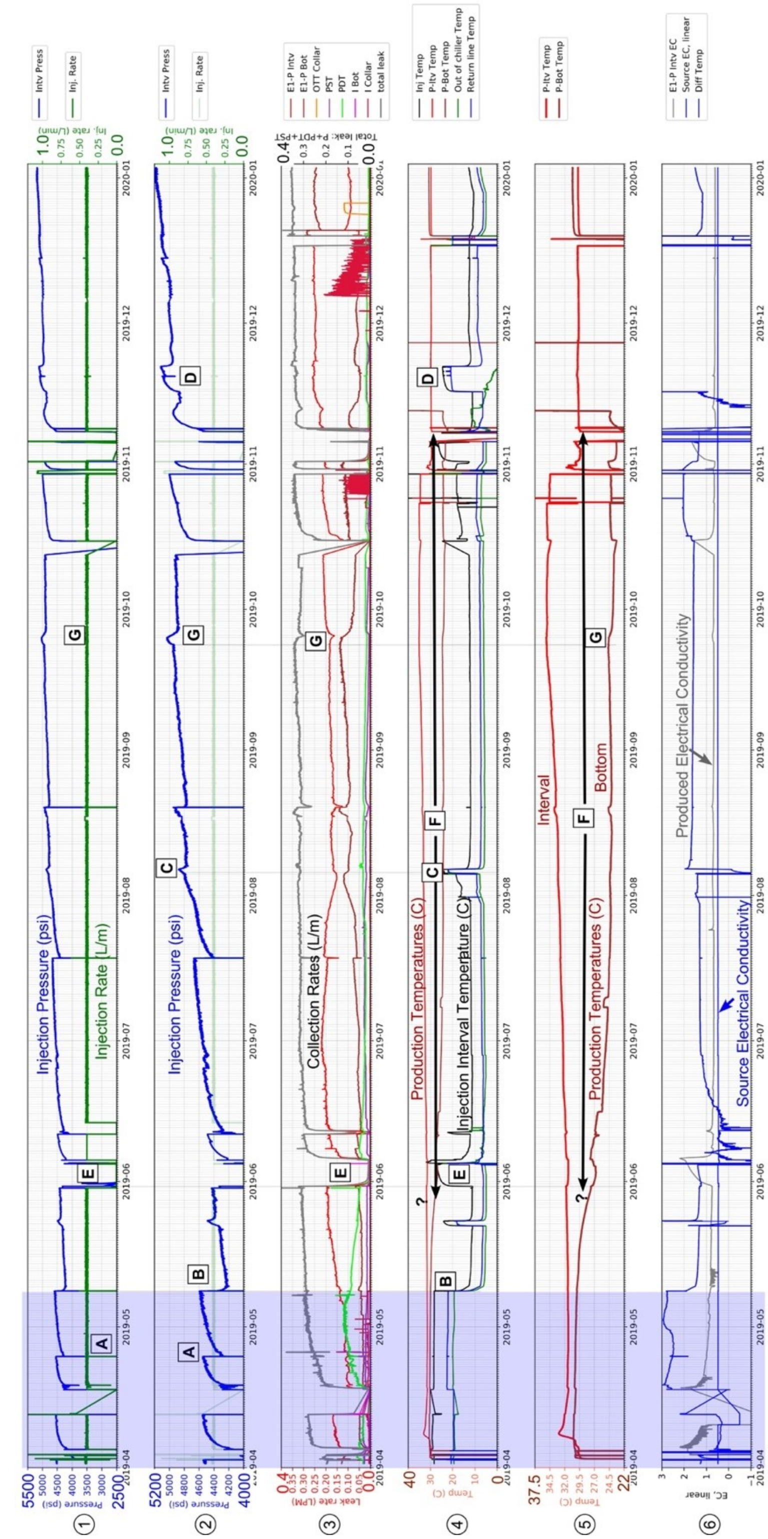

Figure 5. Data summary from long-term flow tests at the 164' Notch. Panels 1 and 2 show the injection pressure and injection rate; Panel 3 shows the out-flow rates from different wells and two isolated segments in well E1-P; Panels 4 and 5 show the injection interval, production interval, and bottomhole fluid temperatures and other temperatures, and Panel 6 shows electrical conductivity (EC) of the source water and the water from well E1-P. Panel 6 also shows the temperature difference between the water leaving and returning to the chiller. The blue shaded region indicates the ambient temperature flow test, whereas chilled water is injected over the rest of the test.

The pump was stopped briefly when chilled water was introduced into the system (see “B” in Panels 2 and 4 of Figure 5). The expected drop in injection pressure was observed, but instead of the injection pressure immediately climbing, the injection pressure dropped for some time before climbing again. 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 when 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 5. When the chiller was shut off, the injected water was warmer. The injection pressure increased as the near-borehole fracture apertures were 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 at “D”.

Pump problems caused a shutdown (see “E” in Panels 1, 3, and 4 in Figure 5), allowing the system to relax for several days. This shutdown induces a temperature transient in the injection interval, in addition to collection flowrate transients from the collection locations. The system returned to the same behavior as before the shutdown after several days of pumping.

Temperatures in the production well (see “F” in Panels 4 and 5 in Figure 5) 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, and in design, the thermistors were electrically isolated from the rest of the system. Resistance checks indicated that there was conductivity where there should not be any, and deconstruction of the thermistors showed swollen epoxy 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 the short term.

“G” in Panels 1, 2, 3, and 5 in Figure 5 show an event that occurred during flow. Without us changing the system (no flow or temperature change 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 one accepts the relative change as real) in the production bottom temperature. This provides an example of the dynamic nature of the system. Cross correlation of data sets may shed more light on this.

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. 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.

Figure 6 shows the microbial community compositions in fluids sampled from boreholes/fractures at or near the site. The data reveal substantial heterogeneity in microbial community profiles despite some of the boreholes/fractures being located as close as 10 m from each other. Three pairs of samples appeared to be highly similar in this dataset, including 1) the duplicate drilling water samples; 2) samples obtained from Fracture A on different dates; and 3) samples from Boreholes OT and PST. Information regarding sampling locations, sample processing protocols and other details can be found in *Zhang et al.* [2019].

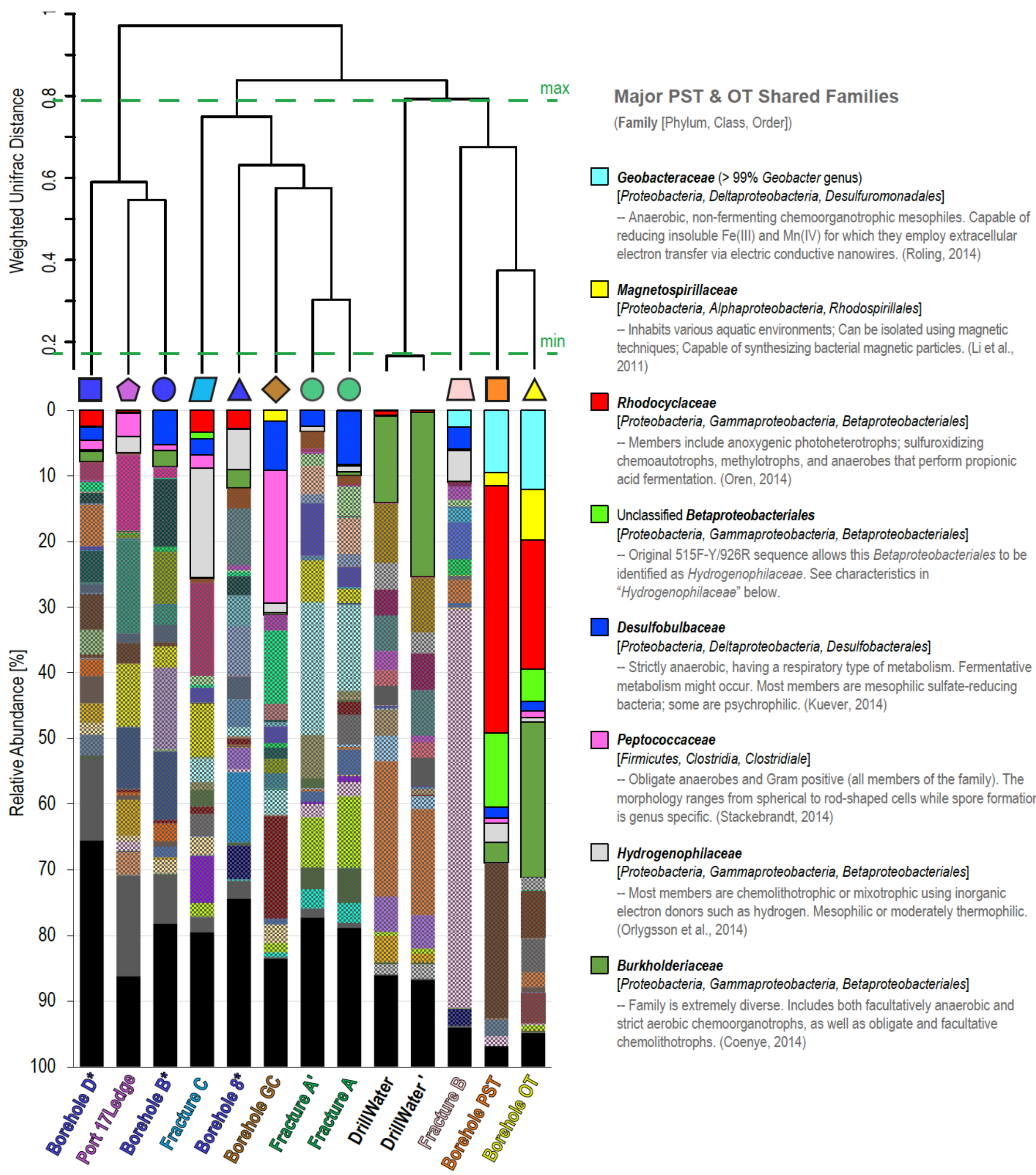

Figure 6. From Zhang et al. (2019). Microbial community composition in water samples obtained via 16S rRNA amplicon sequencing. Full legend list as well as locations of each sample can be found in Zhang et al. (2019). Data reveal substantial heterogeneity across the microbial community profiles of samples spatially distributed throughout SURF 4850 ft level, while communities in Boreholes OT and PST appeared to be highly similar. Bar plot shows the finest classification possible down to the family level. Top left dendrogram is weighted UniFrac Distance calculated between samples visualized via hierarchical clustering. Green dashed lines establish the minimum and maximum weighted UniFrac distance defined for this sample set. Drillwater, Borehole PST, and Borehole OT are from the EGS Collab, others are from other locations on the 4850 level at SURF.

PROJECT LEARNINGS

Project learnings largely fall into three categories, scientific findings, practical lessons, and management approach.

Scientific Findings

<u>Poroelasticity</u>

Poroelasticity appears to play an important role in the response of the rock-fracture system to fluid circulation. As seen in Figure 5, poroelasticity likely dominates the evolution of the permeability of the hydraulically propped fractures. This effect might be expected at FORGE and in EGS systems.

Thermoelasticity

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 prior to the observation of the poroelastic effect. This effect should be expected at FORGE and in EGS systems where cooler water will be introduced into hot rock.

Local geology

A number of local geology effects have been observed to affect stimulation and flow behavior. kISMET drilling showed few fractures, however EGS Collab drilling identified many fractures, particularly in the lower 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 is likely 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 more 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 and fracture orientations 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; *Chi et al.*, 2020; *Kneafsey et al.*, 2019]. 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 can be explained by the Joule-Thomson effect and the sudden decrease in water pressure upon entering the well. In addition, the known location of the fracture intersection with the monitoring well indicated by the DTS provided a comparison point for the inversion of data from the microseismic monitoring array, indicating that the inversions provided accurate event locations.

Practical lessons

The EGS Collab project benefits from exceptional characterization data, but characterization is always incomplete. The best characterization data are those that can be *sufficiently* analyzed and reported to make decisions in an *actionable* timeframe. This requires 1. development of data analysis workflows and automation prior to the acquisition of data, and the general understanding that the initial analyses are preliminary, and 2. the commitment to rapidly screen and provide data to the community. Imperfect-yet-reasonable data now are more valuable than perfect data provided after a decision is required. Visualization of complex data is required, and innovative visualization methods are very important for bringing the truth out. We have developed a number of these workflows making data useable. Some data has not been interpreted rapidly or the interpretations have not been presented. We are trying to minimize these occurrences.

All characterization and monitoring tools need to be properly tested and calibrated. The behavior (response) of the instruments should be estimated for the environment it will be applied in. The layout of sensors used for monitoring should be optimized using the same evaluation methods that will be used to analyze the data. Although this was performed in general, installed instruments may exhibit different characteristics based on their deployment (e.g. potting a geophone in a metal cylinder and grouting the cylinder into a borehole results in differences in the geophone response). The method of instrument deployment requires good engineering and testing considering their effect on sensor operation and interference with the test bed. Grouts, clamps, tubes, and wires should be tested in advance with the conditions and duration of the project considered.

By deploying a diverse set of geophysical monitoring tools in 3D arrays, we were able to investigate new signatures (or null results) for each phase of Experiment 1. This 3D multi-phenomenological monitoring allowed our understanding to evolve in a more rigorous way, where even null results were important for understanding testbed evolution. Another finding was that some relatively ‘low-tech’ methods yielded extremely fruitful results that complimented/verified geophysical observations. For instance, deployments of a downhole video camera in the open boreholes produced real-time video imagery that proved extremely valuable in verifying locations and characteristics of fracture/flow (both natural and induced) connectivity in the wells. Such a deployment of diverse tools is not always feasible but was done here to build confidence in results from less-diverse deployments.

The EGS Collab project has collected hundreds of TB of data, thus data handling and management are not trivial. The majority of data management on the project is facilitated by the Open EI Data Foundry and systems designed for use on this and other projects [*Weers et al.*, 2019; *Weers et al.*, 2018]. The lack of data management problems stems from hand-in-hand interactions between data collectors, data users, and data managers. The amount volume of acquired data is itself a challenge to process and interpret, but this team is dedicated to examining the full suite of acquired data sets.

Flexibility in test bed set up and instrument deployment should be maximized in design and during construction.

Healthy questioning of data and assumptions, and checks of appropriate data processing and corrections have helped identify issues with data sets. Having a diverse team of both field experimentalists and modelers helps promote discussions on data quality, and led to the identification of problems with field measurements that may have remained undetected. Thus, issues/assumptions with borehole orientations, tracer behavior and injected masses, flow rates, and temperature measurements (both DTS and thermistor) have been identified and rectified as the project has progressed.

Management Approach

The EGS Collab team is large. In spite of that, we have leveraged open discussions and data access to facilitate scientific discoveries. Significant effort has gone into communication. Communication across this large team was optimized by bringing the field experimentalists and modeling experts together for discussions and decision making. These close ties have been invaluable in the direction of the project. Experimentalists involved in the modeling added realism to models and aided in focusing questions to make the tests implementable, and modelers involved in field discussions improved the nature of the tests being performed making sure the most useful data are collected. For field tests, the project used high network connectivity, virtual team collaboration software, excellent remote sensor display, cloud data exchange, and edge processing. This resulted in pooling widely dispersed expertise for rapid interpretation, as well as improved engagement and resulted in the broader team being involved virtually and close to real-time for substantial periods of activity. Additionally, we were able to minimize our presence at SURF and reduce cost by making as much of our system operable remotely. Storms affected remote operations, and having excellent local teammates allowed rapid resets when needed. Our communication effort has led to most efforts being in line with project goals, and collection of more relevant and useful data.

It takes time for the truth to emerge even though it may appear obvious in hindsight. Understanding, planning, and minimizing the time for truth to emerge is important. Preconceived notions tend to guide initial attempts to understand system behavior where multiple causes may be possible. We have had some success in challenging preconceived notions, however we would benefit from additional challenges. Discarded ideas should be recalled however, as they may ultimately show promise. For example, in this project, the effect of leakoff was not initially fully appreciated however it is a significant factor in determining propagation rate. In addition, it often takes multiple people having different perspectives to connect the dots. Having the data available and visualized facilitates extracting processes when viewed and discussed by people from various disciplines. Inferring the probable importance of poroelastic effects took a significant amount of time and repeated tests, and many people viewing the data. *Timely sharing of preliminary, immature results and thoughts is particularly important,* because the group of researchers is from diverse disciplines, and these thoughts and results often trigger additional ideas and thoughts, and bring knowledge in from the different disciplines.

CONCLUDING REMARKS

A number of stimulations and flow tests have been performed for the EGS Collab Experiment 1 and this experiment will be ending soon. Our stimulations were successful in connecting 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 has been injected for about 9 months, but decreases in the outlet temperature have not been observed. This is consistent with early predictions [*Winterfeld et al.*, 2019; *Zhang et al.*, 2018]. Flow tests have shown clear thermoelastic effects, indicated by a lowering of the injection pressure at constant flow for 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.

To the extent possible, flexibility in test bed set up and instrument deployment should be maximized in design and during construction to enable better responses to things that may happen. All stakeholders should provide input to aid in optimizing the test bed. The best characterization data are those that can be used to make the needed decisions. This requires reasonable and timely interpretation, and visualization. For sensors, proper calibration and understanding of sensors in the environment they will be deployed including the sensor clamping or grouting and predeployment evaluation of sensor placement is required. Multiple diverse geophysical tools can be used to obtain better system understanding and confidence in the interpretations. Complementary monitoring technologies that capture both transient (e.g.: microseismic) and longer-term flow evolution (e.g. DTS) should be combined to reduce uncertainty. Consideration of data handling prior to gathering the data will make distribution and analysis easier.

Open discussions between investigators from multiple disciplines (either face-to-face or using virtual team collaboration software), easy data access, and rapid data visualization have been extremely valuable to the project, making it easier to connect the dots. Timely sharing of preliminary results, thoughts, and models is extremely important in the analysis of test behavior. Group discussions help in the identification and evaluation resulting in more likely process explanations. Remote test operation relying on real time sensor display allows for rapid response from comfortable quarters, and reduces exhaustion from frequent field work. Frequent communication between experimentalists and modelers aids in optimizing the collection of appropriate, high quality, and useable data.

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 the early summer 2020, and hope to apply our lessons learned to gain better understandings informing EGS.

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