GRC Transactions, Vol. 42, 2018

EGS Collab Project Experiment 1 Overview and Progress

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Keywords

Enhanced Geothermal Systems, EGS Collab, Stimulation, crystalline rock, Sanford Underground Research Facility, coupled process modeling, experimental, field test, flow test

ABSTRACT

Enhanced Geothermal Systems (EGS) offer the potential to extract and use large quantities of clean energy, but questions remain on reservoir creation and sustainability. The EGS Collab project, supported by the US Department of Energy's Geothermal Technologies Office, is establishing a suite of highly monitored and well-characterized intermediate-scale (~10-20 m) field test beds along with fracture stimulation and

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interwell flow tests to better understand processes that control formation of effective subsurface heat exchangers. EGS Collab tests will provide a means of testing tools and concepts that could later be employed under geothermal reservoir conditions at DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) or enhanced geothermal systems. Key to the project is using numerical simulations in the experiment design and interpretation of results. Our first set of experiments is underway at the Sanford Underground Research Facility (SURF) in South Dakota. To date, stepwise stimulations have been performed at two locations, with the final stimulation connecting our injection and production wells. Numerous data have been collected and are currently being analyzed.

1.0 Introduction

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as an indigenous renewable energy resource supporting the energy security of the United States. The US Geological Survey (USGS) has estimated that EGS resources in the western US could exceed 500 GWe, significantly surpassing the resource base hosted by conventional hydrothermal systems (Williams et al., 2008). When considering the entire United States and utilizing higher resource recovery factors, (*Augustine*, 2016) provided an EGS resource estimate that is ten times larger than the USGS evaluation. In spite of these resource estimates, there are technological challenges associated with extracting and utilizing this resource that will need to be addressed including: (1) lack of a thorough understanding of techniques to effectively stimulate fractures in different rock types and under different stress conditions, (2) inability of techniques to image/monitor permeability enhancement and evolution at the reservoir scale to 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 early thermal breakthrough, and (5) lack of scientifically-based long-term EGS reservoir sustainability and management techniques.

The EGS Collab project was initiated by the DOE Geothermal Technologies Office (GTO) to facilitate the success of FORGE (https://www.energy.gov/eere/forge/forge-home). This project will utilize readily accessible underground facilities to refine our understanding of rock mass response to stimulation at the intermediate scale (on the order of 10 m) for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches as well as novel monitoring tools. This project will focus on understanding and predicting permeability enhancement and evolution in crystalline rocks including how to create sustained and distributed permeability for heat extraction from the reservoir by generating new fractures that complement existing fractures. The project is a collaborative multi-lab and university research endeavor bringing together a team of skilled and experienced researchers and engineers in the areas of subsurface process modeling, monitoring, and experimentation to focus on intermediate-scale EGS reservoir creation processes and related model validation at crystalline rock sites (*Kneafsey et al.*, 2018a).

The EGS Collab project has planned three multi-test experiments to increase understanding of hydraulic fracturing, shear stimulation, and other stimulation methods. Modeling will support experiment design, and post-test modeling will examine the effectiveness of and improve the array of modeling tools. Experiments will begin with hydraulic fractures and proceed to shear stimulation of natural fractures and fracture networks with increasing complexity. We will test a suite of characterization methods potentially useful for EGS systems as well as other methods available to improve understanding (*Knox et al.*, 2017). These include a range of geophysical and hydraulic measurements including tracer tests, that can define the effective conducting surface area for heat exchange and determine the flow rate limitations for sustaining production well temperatures (*Doe et al.*, 2014; *Zhou et al.*, 2018) We will also develop new monitoring methods that are currently unable to work under geothermal reservoir conditions. One key to the project is a thermal circulation experiment that will validate predictions based on field data and stimulations.

2.0 EGS Collab Project Objectives

Project objectives

The EGS Collab is a team of researchers from eight national laboratories, six universities, industry and research partners, and the Department of Energy, working to better understand stimulation and related processes (*Kneafsey et al.*, 2018a). The EGS Collab will provide the THMC modeling community with rich stimulation and fluid flow data sets that will be used to *improve and validate the capabilities of predictive models* that will be employed to support FORGE and EGS projects. The intermediate scale of these experiments allows for proximal monitoring that will be accomplished through multiple boreholes in the immediate vicinity of the stimulation leading to high-resolution geological and geophysical characterization of the rock mass before, during, and after stimulation. Together modelers and experimentalists design field tests aimed at providing the key perturbation-response feedback information needed to constrain mechanistic models of coupled THMC processes, e.g., the degree to which shear offset on an existing fracture increases the permeability of the fracture. Development of new modeling tools is not a primary goal of the project, but will naturally occur as more thought goes into understanding processes (*Wang et al.*, 2018). Exercising the modeling tools will lead to the development of new concepts and questions to be answered (e.g. .

3.0 EGS Collab Test Bed 1

3.1 The Sanford Underground Research Facility

Evaluation of a number of sites led the team to choose the Sanford Underground Research Facility (SURF) in Lead, South Dakota as the EGS Collab project experimental site (Figure 1). SURF is located in the former Homestake gold mine and is operated by the South Dakota Science and Technology Authority. It is the host to a number of worldclass physics experiments related to neutrinos and dark matter, as well as to geoscience research projects (*Heise*, 2015). As a mined underground research laboratory, SURF offers a number of advantages to allow the EGS Collab project work to move forward quickly, including cost-effective proximal monitoring of a crystalline rock mass before, during, and after stimulation through multiple boreholes drilled from an underground tunnel.

A priority was placed on assuring the selected site had accessible rock under realistic in-situ stress conditions and that these conditions could be accessed at reasonable cost. While moderate temperature would be advantageous and SURF is at low temperature (~30-35°C) at the designated testing depth of ~4850 feet (~1.5 km), locating a site that offers both realistic temperatures and stress involves relatively deep drilling, which is costly and does not facilitate detailed characterization and monitoring, and would thereby prevent us from achieving the EGS Collab objectives. Several options exist to approximate temperature-induced effects in the field (e.g., using chilled or heated brines to induce a differential temperature) or complementary high-temperature laboratory experiments (*Smith et al.*, 2018). Similar options do not exist to replicate stress at the desired scale. At depths of approximately 1.5 km, SURF satisfies the stress criterion. Additionally, SURF is well characterized (e.g., Hart et al., 2014) with robust installed infrastructure (e.g., ventilation, power, water and internet) and maintains an excellent staff dedicated to scientific research support, in addition to health and safety practices and all necessary environmental permitting.

3.2 Leveraging the kISMET project

SURF was the location of the kISMET project, providing a significant amount of relevant data and site understanding (*Oldenburg et al.*, 2017). The kISMET (permeability (k) and Induced Seismicity Management for Energy Technologies) project objectives were to conduct modeling and field experiments to measure stress orientations and magnitude, conduct hydraulic fracturing in crystalline rock to enhance permeability, evaluate different monitoring techniques, and monitor associated induced seismicity. The kISMET project drilled and cored 5 near-vertical downward boreholes from the 4850 level of SURF resulting in a five-spot configuration at 50 m depth, with the central 100 m deep NQ borehole used for the stress and hydraulic fracture experiments and the four surrounding 50 m deep HQ boreholes used for monitoring purposes. After drilling the boreholes, site characterization was performed by careful examination of the core, running a suite of imaging logging tools in the boreholes, and conducting baseline Electrical Resistivity Tomography (ERT) and Continuous Active Seismic Source Monitoring (CASSM) measurements. Stress measurements were conducted in the lower portion of the central borehole, followed by a longer-term hydraulic fracture experiment at a depth of 40.23 m below the 4850 level drift invert. The shear fractures generated from these tests (Figure 2) indicate that S_{hmin} is about 21.7 MPa (3146 psi) and is oriented N-S (355 degrees azimuth) with a plunge slightly NNW at 9° (*Kneafsey et al.*, 2018b; *Wang et al.*, 2017). The vertical and stress magnitude is estimated to be ~42-44 MPa (6090-6380 psi) for the depth of testing (~1530 m), and the horizontal maximum stress is estimated to be 80% of that (Singh, 2017 personal communication]). Review of previous borehole stress measurements and stress indicators in other boreholes on the 4850 level was also conducted.

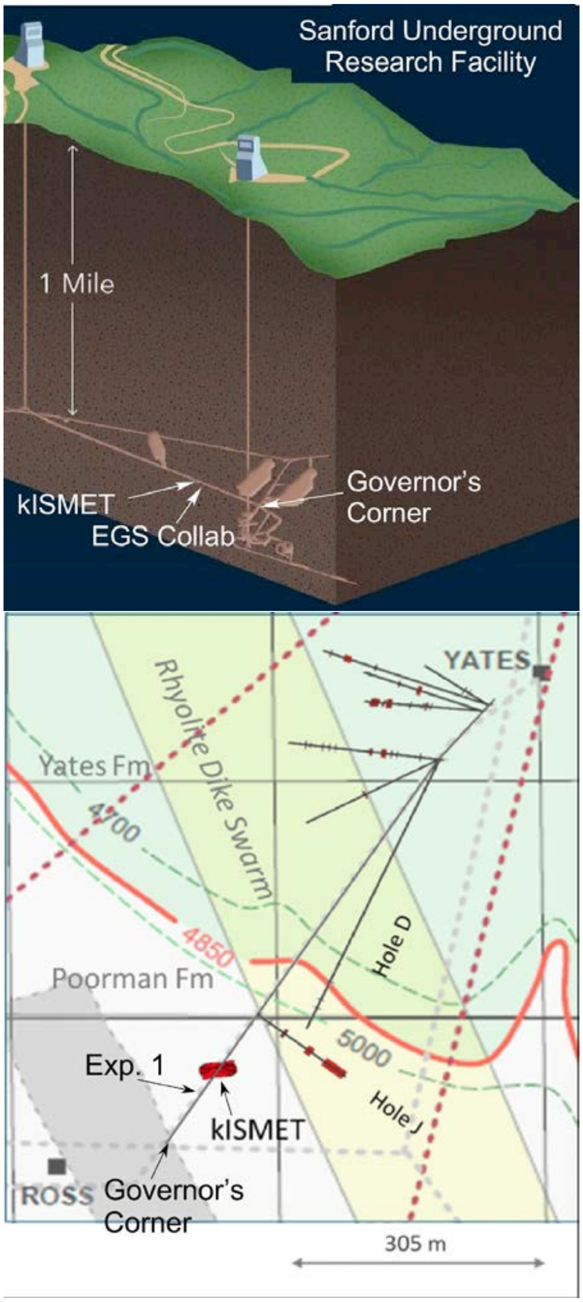

Figure 1: a) Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, and the locations of the kISMET experiment, and Experiment 1. b) Geologic map of the 4850 level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

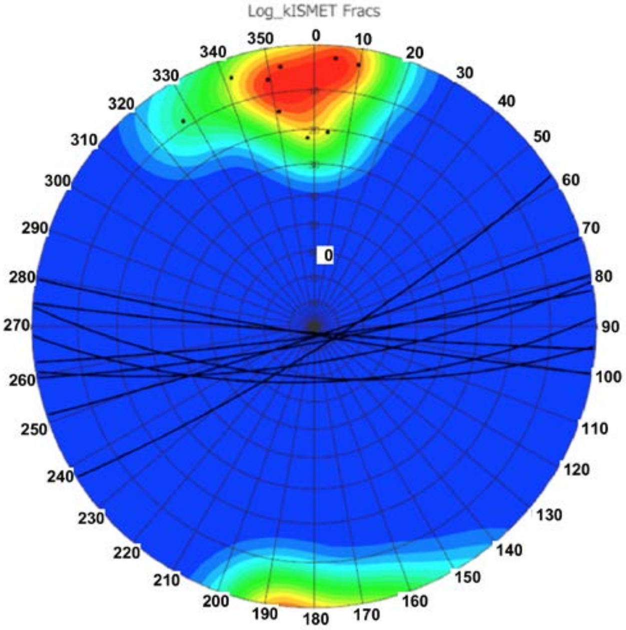

Figure 2: Orientation of fractures in kISMET 003 borehole. The stress orientations for the nearby Experiment 1 site are presumed to be similar to those obtained during kISMET tests.

Experiment 1 Description and Unexpected Conditions

EGS Collab Experiment 1

The EGS Collab Experiment 1 site was chosen in the vicinity of the kISMET site along the West Drift on the 4850 Level (Figure 1) for the following reasons:

- Well-characterized geology of the site (known rock type, fabric, stress orientations)
- Site readiness status (good ground support, availability of power, water, internet), allowing experiment to be conducted sooner and at lower cost to the project
- Appropriate rock (relatively homogeneous, minimally fractured) well suited for planned hydraulic fracturing experiment
- Drift size and orientation conducive for drilling planned boreholes and carrying out subsequent experimental activities

A number of modeling studies have been conducted to estimate the volume of fluid for stimulation, and to estimate possible fracture apertures and extents (*Fu et al.*, 2018). Initial modeling efforts (*White et al.*, 2017; *White et al.*, 2018) have focused on a number of initial questions to guide experiment design including 1) preferred orientation for the stimulation borehole, 2) anticipated number and magnitudes of seismic events during hydraulic stimulation, 3) flow rates and pressures for the circulation experiments to prevent fracture propagation, 4) circulation duration required to achieve measureable temperature changes in the production borehole, 5) the role of the production well in preventing fracture propagation to the drift, 6) the orientation of a hydraulic fracture from the unaltered or notched injection borehole drilled in the direction of σ_h, 7) the impact of notch geometry on stimulation pressure and near wellbore impedance, 8) effect of the thermal profile around the drift, 9) the alteration of the stress state in the experimental volume via mechanical and thermal alteration from the mine workings and drift cooling, and 10) anticipated shape and arrival time in terms of injected fluid volume of the hydraulically generated fracture under the mechanically and thermally altered stress state.

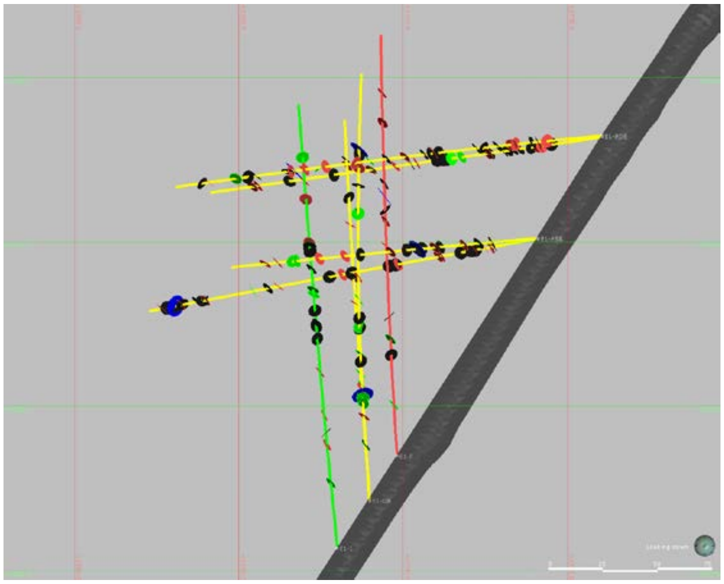

Figure 3: Plan view schematic of boreholes for Experiment 1 location along the West Drift on the 4850 level of SURF. Black disks represent healed fractures identified during core and borehole logging. The green line represents the stimulation well, the red line represents the production well, and yellow lines represent monitoring wells. Orientation of stimulation and production boreholes is approximately parallel to S_{hmin}.

The borehole configuration for the first experiment was developed (Figure 3) and refined based on available data and team feedback. This design is based on having sub-horizontal stimulation and production boreholes dipping slightly downward that are oriented in the direction of the minimum principal stress (perpendicular to the orientation of the expected hydraulic fractures), and that are spaced 10 meters apart (*Morris et al.*, 2018). A suite of monitoring boreholes will allow for sensors to be located near the location of the anticipated fracture plane, facilitating monitoring of fracture propagation and fluid flow within the fracture system. Numerical modeling of sensor outputs for expected events during stimulation was used to specify the number and location of seismic and acoustic emission sensors, and ERT sensors (*Knox et al.*, 2017).

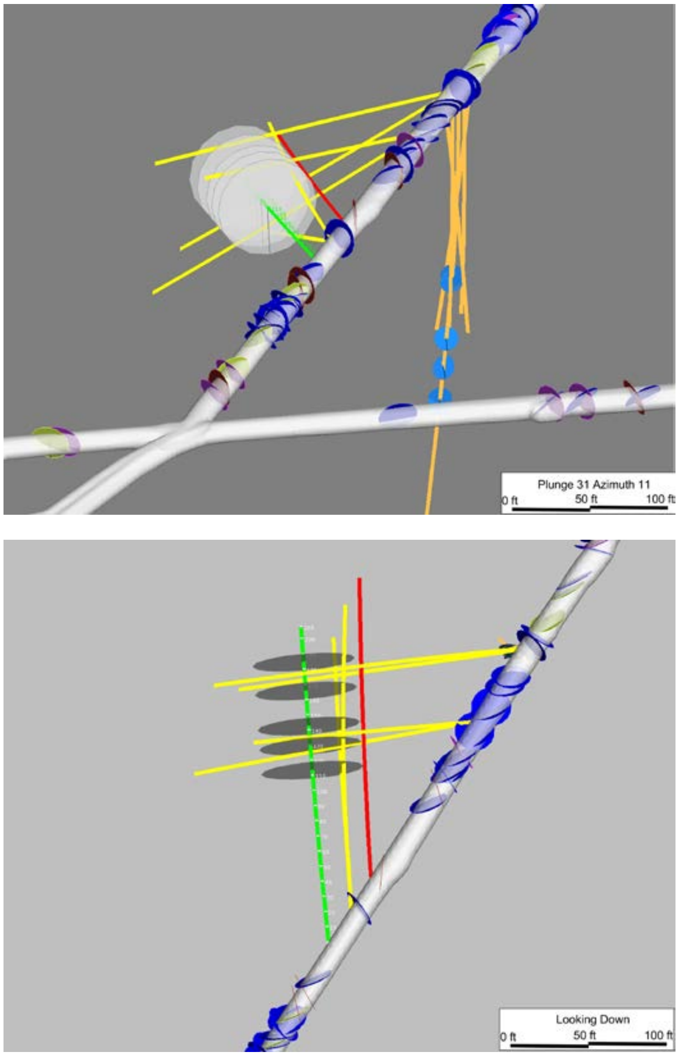

Figure 4: Oblique views of the as-built Experiment 1 test site. Drifts are shown as the wide white tubes. The subvertical kISMET wells are orange, and the stress measurement tests performed in k003 are shown as light blue circles. Various colored circles along the drift indicate observed fractures (mapped by Nuri Uzunlar). The yellow lines represent the monitoring boreholes, and the green and red lines represent the injection and production wells respectively. Gray circles indicate potential stimulated fractures from placed notches. Top: View from above right of Governor's Corner. Bottom: ~Top view.

We have developed and are using a geologic framework model using Leapfrog (Aranz Geo Limited). Our incorporated data includes recently obtained measurements, geologic data contained in the Maptek Vulcan database for SURF(e.g., Hart et al., 2014), available geotechnical reports, the kISMET study (*Oldenburg et al.*, 2017). From this we created three scales of geologic models: a mine scale model, an intermediate scale model that includes multiple drift levels, and a more detailed model that encompasses the immediate area around Experiment 1 for visualization and simulation (Figure 4). Additional geologic information will be included in the models as it becomes available. The geologic framework model is important in constraining the grid block properties for the coupled process models simulating the EGS Collab experiments, visualization, and providing a more uniform basis for model comparison.

Borehole logging included resistivity, full-waveform sonic, temperature, conductivity, optical televiewer, and acoustic televiewer, and data are being analyzed. Over 450 meters of core has been retrieved, logged, and photographed to identify foliation, veining, bedding, fractures, and variations in mineralogy. All of the 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 are calcite, dolomite, and ankerite. The rock is highly deformed and has veins/blebs of carbonate, quartz, and pyrrhotite, with minor pyrite. Other mineral phases (in addition to those listed above) include graphite and chlorite. Optical and acoustic televiewer logs will be used to look for borehole breakouts and to identify any natural fractures within the boreholes. Baseline seismic tomography, ERT and CASSM surveys have been conducted prior to stimulation and results are currently being analyzed. The existing kISMET boreholes have been utilized to measure temperature gradients away from the drift walls. To the extent possible, these data are being integrated into the geologic framework model of the Experiment 1 site.

The detailed site characterization together with the array of installed monitoring systems and inversion methods will provide necessary field data needed 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); 2) CASSM (*Daley et al.*, 2007; *Gao et al.*, 2018); 3) ERT in conjunction with dynamic electrical imaging using high contrast fluids (*Johnson et al.*, 2014; *Wu*, 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); 6) fracture aperture strain monitoring using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool (*Guglielmi, Yves et al.*, 2015; *Guglielmi, Y. et al.*, 2013); 7) continuous monitoring of pressure and flow conditions in the injection and production boreholes; 8) tracer tests (*Zhou et al.*, 2018); and 9) wavefield imaging and inversion (*Huang et al.*, 2017; *Knox et al.*, 2016; *Newman and Petrov*, 2018)). Laboratory experiments on selected core samples from the site will measure fundamental physical rock properties needed constrain the coupled process models (*Huang et al.*, 2017).

4.2 Unexpected Conditions

The Experiment 1 site is located only tens of meters from the kISMET boreholes. Observations from these kISMET subvertical boreholes including extracted core led us to think the rock is relatively unfractured, or with healed fractures. Water inflow into some the kISMET holes is on the order of liters/year or less. Our subhorizontal boreholes, however, have identified a number of features. Our subhorizontal boreholes have intersected a number of flowing and nonflowing fractures (*Roggenthen et al.*). Two boreholes intersect a relatively open fracture, as water readily flows between these holes. Another borehole intersects a water-filled or flowing fracture network, and produced water at a low rate for about eight weeks after drilling was completed. The flowrate initially declined, and subsequently increased for a short period following logging. These changing flow rates, in combination with observations of rusty-looking stains on the drift wall where the water drained, leads to the question of the presence of biological and chemical processes (*Osburn et al.*, 2014; *Stetler*, 2015). Analysis of which microorganisms are present, and how they might affect our tests has begun. Another unexpected feature was the intersection of quartz-rich pods within the phyllite – this slowed drilling rates dramatically when encountered.

Stimulations

Initial stress modeling around the injection borehole indicated that fractures were likely to initiate parallel to the borehole and twist about 90 degrees to propagate in the direction of the maximum principal stress (*Abass et al.*, 1996; *El Rabaa*, 1989; *Morris et al.*, 2018). Because of that, researchers at Sandia National Laboratories designed and constructed a drill-steel mounted notching tool to cut a sharp notch in the borehole (*Morris et al.*, 2018). Using this tool, 5 notches were cut in the injection borehole at locations determined from core and borehole logging observations, after 1 was cut at a shallow location in the borehole as a test.

Custom SIMFIP tools (*Guglielmi et al.*, 2015; *Guglielmi et al.*, 2013) were constructed to be employed between inflatable straddle packers in both the injection and production boreholes to measure three-dimensional strains between the packers. The interval between packers including the SIMFIP subassembly on the injection tool is 65 inches. The lower packer in the production hole failed to inflate for the initial stimulations reducing pressure control in that borehole. The production SIMFIP packer had a much larger separation between packers (105 in) to allow for the uncertainty in the fracture propagation direction. The production packer was also outfitted with a number of electrical conductivity probes to identify the location where water flowed into the interval (Figure 5).

The stimulation and flow system was designed to be as versatile, with 3 different pumps. These include a high resolution continuous flow displacement pump system (34 MPa, up to 400 mL/min), an air-driven liquid piston pump (69 MPa, up to 3.2 lpm) and a variable frequency drive triplex pump (48 MPa, up to 13.6 lpm) (*Ingraham et al.*, 2018). The displacement pump and lower resolution triplex pumps were used to stimulate the rock, and the air-driven liquid piston pump was used to inflate the packers.

Initial information from the stimulations is presented here for recently completed fractures. Review of the collected data is under way, so *these data should be considered* preliminary at this time. The initial stimulation was set to occur at the notch at 141.3 feet and the SIMFIP tool was centered on that notch. Our planned stimulation was to initially create a nominal 1.5 m radius fracture by injecting water at 200 ml/min for 9 minutes after fracture initiation and perform an extended shut-in (up to several days if needed). At the 141.3 ft notch, injection behavior indicated that there was some flow around the upper packer, and rapid leakoff into the formation. Later log review of the location indicated that flow may have occurred into an existing (mostly) healed fracture. Optical and acoustic televiewer logs collected under unpressurized conditions for that section of the injection borehole are presented in Figure 6, highlighting observed changes. Some fracturing clearly occurred as shown in Figure 6, perhaps intersecting a nearby natural fracture.

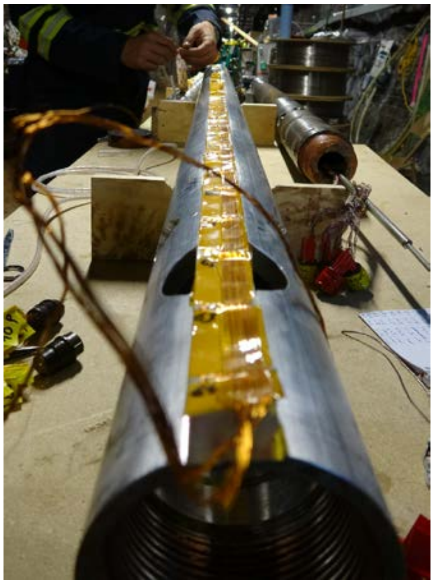

Figure 5: Electrical conductivity probe subassembly for production well SIMFIP tool.

Because of leakage and unexpected pressure behavior at location 141.3, we centered the stimulation packer on the next deeper notch at ~164.3 ft and implemented our stimulation protocol. We initially did not select this location because of fractures that potentially cross cut the ideal stimulation fracture and near the production well. We initially fractured to a nominal 1.5 m and shut in, followed by a step test, driving the fracture to a nominal 5 meters and shut in, then finally drove the fracture to intersect with the production well. Injection volumes, pressures, and rates are presented in Table 1.

In the initial stimulation, we flowed at 200 mL/min and the pressure rose, rolling over (stimulating) at a pressure just under 25 MPa (Figure 7a). At constant flow, the pressure fell before gently rising to over 25 MPa at the conclusion of that injection. A long shut in was desired to understand the rock and stress conditions. The shut in was initiated, but unfortunately, a power abnormality occurred after the team returned to the surface resulting in the loss of some data.

The next day, the step test was performed. The interval was pressurized to 6.6, 13.4, and 20.3 MPa and flow rate recorded, after which flow was stepped from 0 to 100 to 200 to 400 mL/min and pressure was recorded. After the injection of 23.5 liters, the fracture was shut in. During the flow at 400 mL/min, pressure increased to 26.3 MPa, after which it declined for the duration of the injection to about 25.9 MPa before shut in (Figure 7b). The next day, the fracture was driven to the production well by pumping 80 L of water at rates up to 5 L/min. Injection pressure reached 27.3 MPa before leveling out to 26.8 MPa when shut in (Figure 7c). In addition to intersecting the production well, the fracture intersected Monitoring Well OT. This was indicated in several data streams, including hydrophones and distributed temperature sensors. Some water flowed up Monitoring Well OT, requiring repairs on that well.

Optical and acoustic televiewer logs for the 161.3 foot section of the injection borehole logs collected under unpressurized conditions are presented in Figure 8, highlighting observed changes. A number of changes are apparent, identified by arrows. No fracture matching initial conceptual models is observed under unpressurized conditions.

Electrical conductivity sensors on the production packer assembly gave a preliminary indication of the location where the fracture broke through into the production well. The production packer assembly was removed from the well, and the water was removed from the well. A camera was installed in the well and a flow test performed. Water entered the well in jets from pinhole-size regions that are thought to lie on existing fractures (Figure 9). Figure 10 shows a schematic of the stimulation

Table 1. Flow, pressure, and volumes associated with the stimulations.

Test	Injection Volume (L)	Cumulative Vol. (L)	Stable Rate (L/min)	Propagation Pressure Prior to Shut-in (MPa [psi])	Instantaneous Shut-In Pressure (ISIP, MPa [psi])
Drive to 1.5 m	2.1	2.1	0.2	25.43 [3688]	25.37 [3679]
1.5m Step Test, Drive to 5 m	23.5	25.6	0.4	25.95 [3763]	25.82 [3744]
Drive to Production Well and Breakthrough	80.6	106.2	5	26.88 [3898]	25.31 [3670]
Flow Test 1	77.9	184.1	4.55	26.71 [3873]	25.36 [3678]
Flow Test 2	119.3	303.4	4.55	26.74 [3878]	25.14 [3646]

Concluding Statements and Lessons Learned

A significant amount of work has gone into predicting, planning, constructing, and executing this series of tests to date and a significant amount of work analyzing data has begun. A diverse and talented group in the field and office carefully thought through many possible options, events, features, and processes, and created many conceptual and numerical models. High quality data have been collected and are being collected and analyzed to interpret observations made during our tests. These models will be challenged with data to understand what happened, and to validate and improve the models.

Success in the EGS Collab project is in achieving scientific goals, therefore collecting lessons learned is very important and will be included in project papers. These include understanding the precision of measurements needed for the analyses required. Instrument location errors occur from simple measurement errors along a conveyance pipe, nonuniform conveyance pipe lengths, and very small angle errors in the orientation of the boreholes affect data interpretation. Simple location registration errors are common as many logging techniques, drillers, and researchers may use different fiducial marks as their “zero” location, and the cables conveying these instruments may vary slightly from run to run. This problem is not unique to EGS Collab.

The EGS Collab has completed one stimulation connecting two boreholes and collected data using numerous techniques. The created fracture will be tested using a number of tracers and thermal testing to understand its properties. Additional hydraulic fracture stimulations and quantifications will be required, as well as shear stimulation and fracture set quantifications. Preparation for these other tests has begun, and data is being managed using the EGS Collab data system (*Weers and Huggins*, 2018). Data from the tests will become available as soon as possible.

ACKNOWLEDGMENTS

This material was based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office, under Award Number DE-AC02-05CH11231 with LBNL and other awards with other national laboratories. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. We thank the drillers of Agapito Associates, Inc., for their skill and dedicated efforts to create our test bed boreholes. The research supporting this work took place in whole or in part at the Sanford Underground Research Facility in Lead, South Dakota. The assistance of the Sanford Underground Research Facility and its personnel in providing physical access and general logistical and technical support is gratefully acknowledged. The earth model output for this paper was generated using Leapfrog Software. Copyright © Aranz Geo

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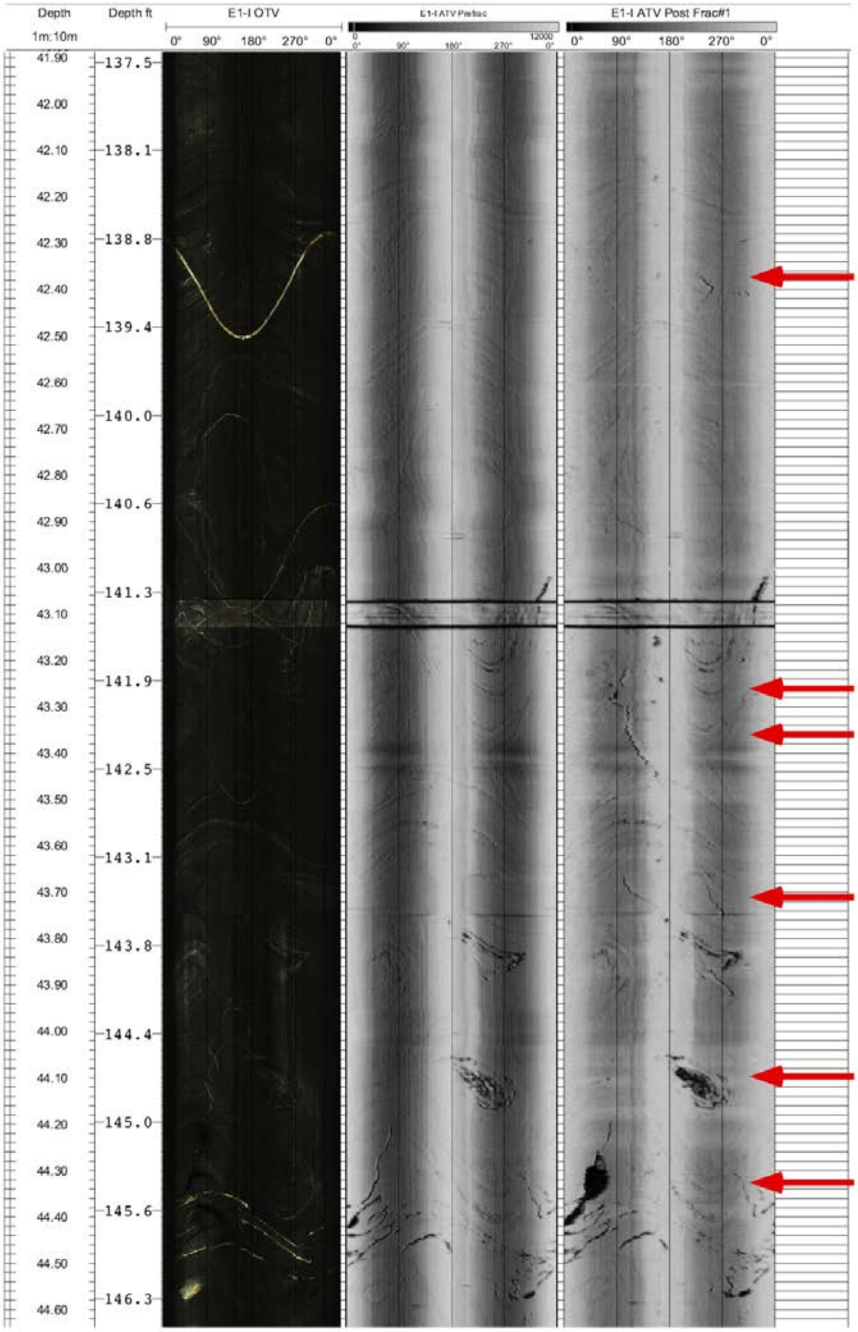

Figure 6. Optical televiewer log (left), acoustic televiewer log prior to stimulation (center) and acoustic televiewer log post stimulation for notch (right) at ~141.3 feet. Arrows indicate locations where the pre- and post-test acoustic logs are obviously different indicating a change at that location.

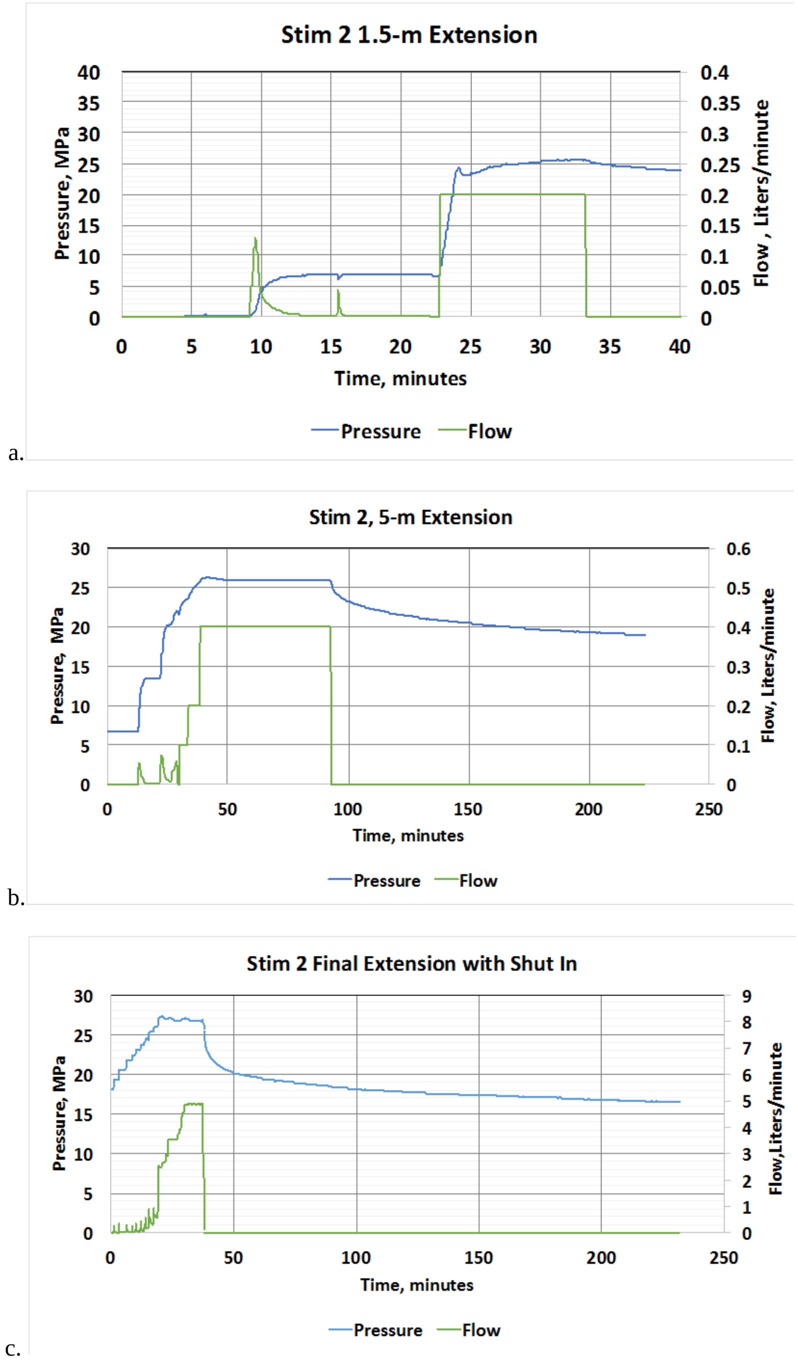

Figure 7. Pressure and flow during stimulation. a. initial stimulation, b. drive to 5 m, and c. drive to production well.

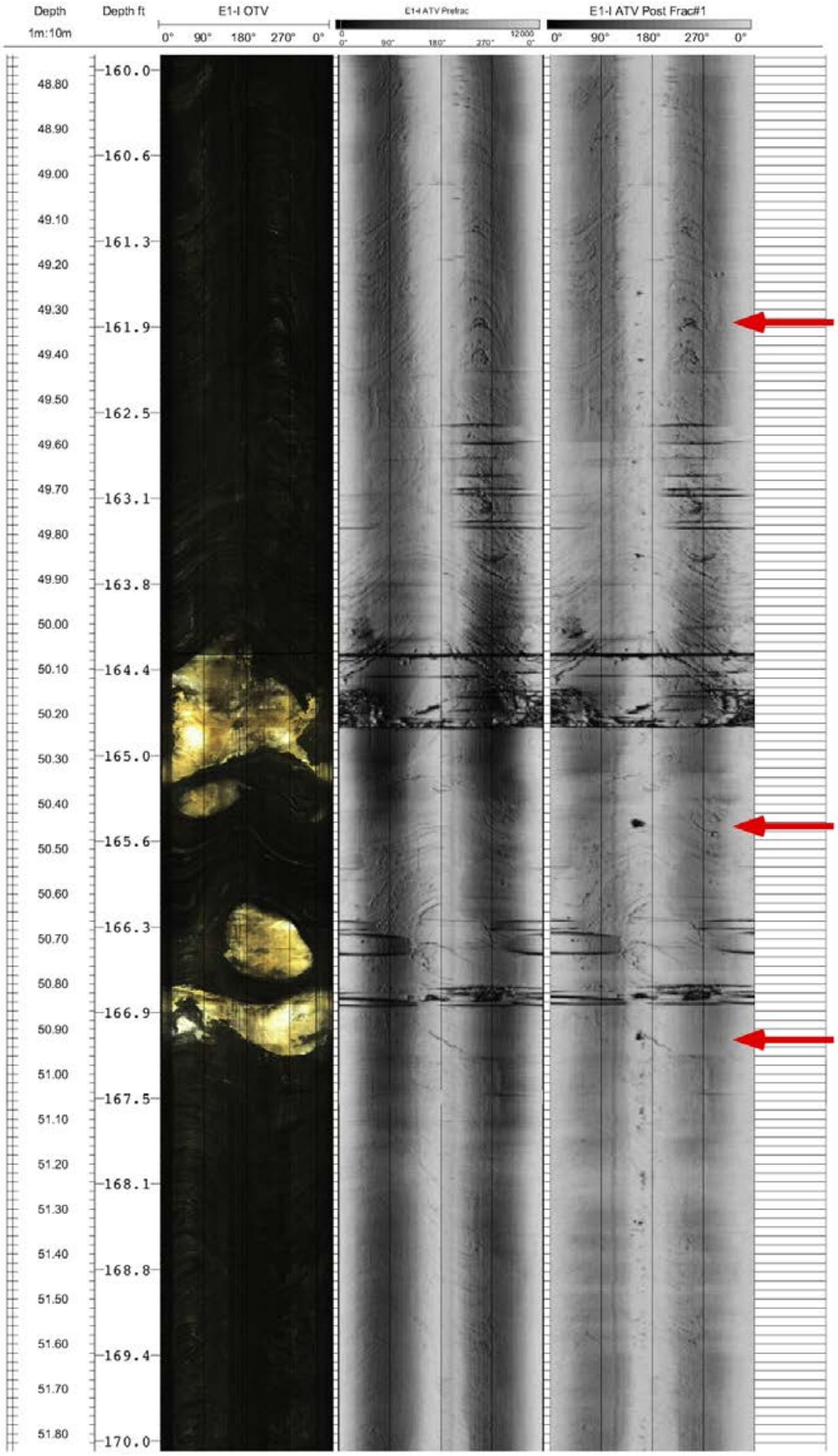

Figure 8. Optical televiewer log (left), acoustic televiewer log prior to stimulation (center) and acoustic televiewer log post stimulation (right) for notch at ~164.3 feet. Arrows indicate locations where the pre- and post-test acoustic logs are obviously different indicating a change at that location.

Figure 9. Jets of water squirting into the production well during a flow test.

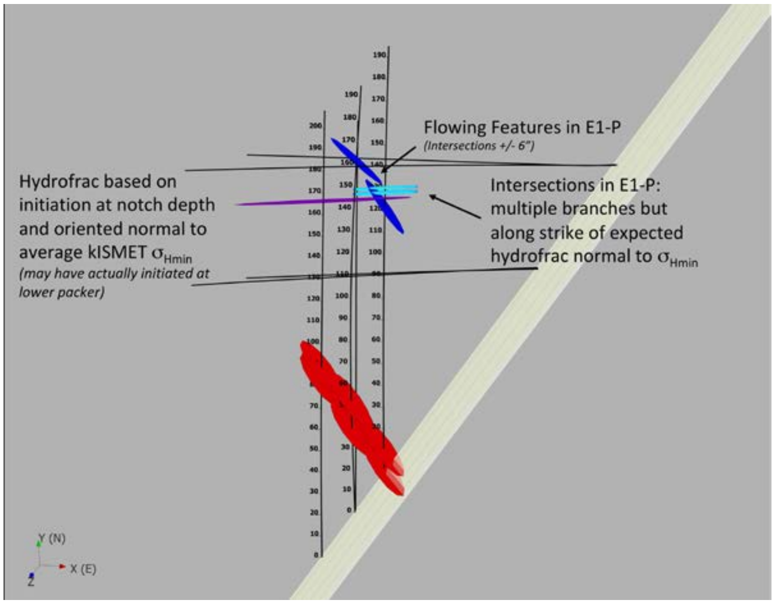

Figure 10. Schematic of the site and stimulation, assuming a penny shaped fracture. The view is from the top and the drift is light gray. The injection hole is the vertical line on the left, the production hole is the vertical line on the right, with Monitoring Wells OT and OB in between. The stimulation fracture is indicated by the purple ellipse. Dark blue circles indicate fractures identified from core and borehole logs. Light blue ellipses indicate possible fractures intersecting the production well where water was observed to flow in. The red disks indicate a group of fractures that may continue and intersect with the drift in a weep zone.

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