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The EGS Collab Project – Fracture Stimulation and Flow Experiments for Coupled Process Model Validation at the Sanford Underground Research Facility (SURF), South Dakota, USA

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ABSTRACT

Successful widespread deployment of Enhanced Geothermal Systems (EGS) will require accurate predictions of flow rates through induced and natural fractures and changes in produced fluid temperatures over time. Complex, heterogeneous fracture pathways can lead to channeling, short-circuiting, premature thermal breakthrough, and loss of injected fluid, thus complicating EGS heat extraction. Field testing of fracture stimulation methods and the resulting fluid flow and heat transfer through these engineered reservoirs can constrain and validate coupled process models needed to design and monitor the performance of EGS. The objective of the EGS Collab project is to establish intermediate-scale (~10 meter) field test beds coupled with stimulation and interwell flow tests to provide a basis to better understand fracture stimulation methods, resulting fracture geometries, and processes that control heat transfer between rock and stimulated fractures. We have developed the first experimental test bed for conducting these experiments at the Sanford Underground Research Facility (SURF), located in Lead, SD, USA. This test bed is located on the 4850 Level (1478 meters below the ground surface) of the former Homestake gold mine in the Precambrian Poorman Formation phyllite. The test bed consists of a stimulation/injection borehole, a production borehole, and six highly instrumented monitoring boreholes. The axes of the injection and production boreholes were designed to be parallel to S_{hmin}, which should cause hydraulic fractures to be preferentially generated perpendicular to the boreholes. After first characterizing the test bed, we have performed a series of hydraulic stimulation experiments at different notched intervals with the goal of creating a series of hydraulic fractures that connect the injection and production boreholes. For these stimulated zones, we have conducted a series of flow, tracer, and heat exchange experiments, and have incorporated these results, along with study of the core and image log data, to create a discrete fracture network model of our test bed. These experiments have been closely monitored using a comprehensive suite of instrumentation consisting of continuous active-source seismic monitoring (CASSM), passive microseismic (MEQ), electrical resistivity tomography (ERT),

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borehole pressure monitoring, in situ borehole deformation monitoring using the novel Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP) tool, and continuous distributed monitoring of temperature, seismicity, and strain using fiber optic cables. These experiments provide a means of testing concepts, tools, and codes that could later be employed under geothermal reservoir conditions at the Frontier Observatory for Research in Geothermal Energy (FORGE) and in future industry-scale EGS projects. Concurrent with the meso-scale experiments, we are advancing our numerical simulation capabilities via novel approaches to applying existing simulators and the implementation of new schemes modifying existing computer codes. Pre- and post-test modeling of each test allows for improved experimental and monitoring design, as well as model prediction and validation. These data are being analyzed and compared with models and field observations to further elucidate the basic relationships between stress, induced seismicity, and permeability enhancement. We will observe and quantify other key governing parameters that impact permeability, and will attempt to understand how these parameters might change throughout the development and operation of an EGS project with the goal of enabling commercial viability of EGS.

1. INTRODUCTION

The development of enhanced geothermal systems (EGS) has the potential to dramatically increase the deployment of geothermal resources in the US and around the world (e.g., Tester et al., 2006; Williams et al., 2008; Augustine, 2016; US DOE, 2019). Such resources are far more abundant and widespread than conventional hydrothermal systems, but require technological advancements in drilling, characterization, monitoring, and reservoir creation and sustainability for widespread development of such resources to be commercially viable. The U.S. Department of Energy's Geothermal Technologies Office (GTO) has launched a series of research initiatives to spur the development of these technologies. The EGS Collab project is an effort on the part of the GTO to establish intermediate-scale (~10 meter) field test beds coupled with stimulation and interwell flow tests to provide a basis to better understand fracture stimulation methods, resulting fracture geometries, and processes that control fluid/heat transfer between rock and stimulated fractures. This suite of well constrained field experiments will also facilitate the use and validation of coupled process numerical models to capture fluid and heat flow, water-rock interactions, and geomechanical processes that result in enhanced fracture fluid flow. One of the objectives of this project is to develop a suite of technologies and numerical modeling approaches that can be tested at the Frontier Observatory for Research in Geothermal Energy (FORGE) to help advance three key research and development challenges associated with EGS: 1) stimulation planning and design, 2) fracture control, and 3) reservoir management (McKittrick et al., 2019).

The EGS Collab team consists of scientists and engineers from nine US DOE National Laboratories (LBNL, SNL, LLNL, PNNL, INL, LANL, NREL, ORNL, and NETL), seven universities (Stanford University, the University of Wisconsin, South Dakota School of Mines & Technology, the University of Oklahoma, Penn State University, the Colorado School of Mines, and Rice University), and three companies (McClure Geomechanics, LLC, TDoeGeo Rock Fracture Consulting, and Mattson Hydrology). This collaborative team is organized into two groups: a field group, which is tasked with testbed development and characterization and the design and implementation of the different field experiments and associated monitoring activities, and a modeling group, which works closely with the field team to help with experiment design and uses numerical models to interpret the field experiment results.

Three main groups of experiments have been proposed by the EGS Collab team. The first set of experiments have been focused on generating hydraulic fractures that would connect an injection well with a production well that are spaced 10 m apart. These fractures would then be utilized in a series of flow tests to assess the fracture properties and heat exchange characteristics of the test bed. The second set of experiments is planned with a focus on shear stimulation of natural fractures, with similar types of tests used to characterize the fluid flow and heat transfer properties of the site. The results of these first two sets of experiments will be used to design and conduct a third set of tests that will utilize alternative stimulation and operation methods to improve heat extraction.

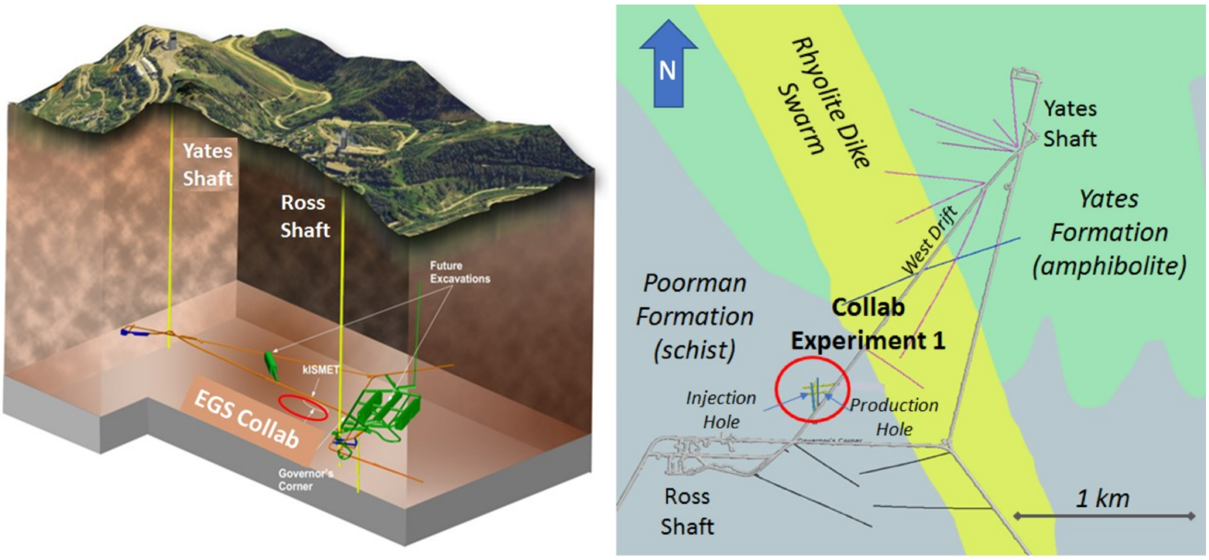


Figure 1: Left) The Sanford Underground Research Facility, depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, the location of the kISMET experiment, and the EGS Collab Experiment 1 site. Right) Geologic map of SURF on the 4850 level (1478 m below ground surface) between the Yates and Ross shafts. The zone of Tertiary rhyolite dikes is depicted schematically – the dike swarm is not continuous. Colored lines coming off of the drifts represent cored boreholes.

The EGS Collab team chose the Sanford Underground Research Laboratory (SURF), the site of the former Homestake gold mine, as the location for conducting the proposed suite of experiments (Fig. 1). The mine workings are located in a sequence of metasedimentary and metavolcanic rocks that were deposited about 2.0 Ga and the gold deposit is associated with sulfide mineralization in the Homestake Formation, an early Proterozoic banded iron formation (Caddy et al., 1991; Frei et al., 2009). This site was selected because it provided access to a deep (~1.5 km) underground facility with stress conditions suitable for the proposed suite of experiments. This site, which also is host to a number of impressive physics experimental facilities (Heise, 2015), has an excellent facilities staff that provides critical logistical and infrastructure support to the field experiments.

2. SITE SELECTION, TEST BED DESIGN, CONSTRUCTION, AND CHARACTERIZATION

2.1 Site Selection

The first key task of the EGS Collab team was to select an appropriate site at SURF to develop a test bed where the initial suite of experiments could be conducted. The team focused their attention to the 4850 level (located approximately 4850 feet (1478 m) below the ground surface), where the infrastructure needed to conduct these experiments (e.g., ventilation, ground support, rail systems, power, water and internet) were already available. Previous geologic and geotechnical studies of this area (e.g., Caddey et al., 1991; Lisenbee and Terry, 2009; Hart et al., 2015) provided ample information regarding the geology of SURF. Three main geologic units are present in this area: 1) the Ross Member of the upper Poorman Formation, consisting of metasedimentary phyllite with abundant graphite, mica, and carbonate; 2) the Yates Unit, an amphibolite metabasalt; and, 3) aphanitic Tertiary rhyolite dikes (Caddey et al., 1991; Steadman and Large, 2016). More detailed geologic investigations, particularly the Permeability (k) and Induced Seismicity Management for Energy Technologies (kISMET) project of the West Drift portion of the 4850 level (Oldenburg et al., 2017; Wang et al., 2017), indicated an area that had relatively straightforward geology and a drift orientation that appeared to facilitate the development of a test bed. Borehole stress measurements from kISMET indicated that the minimum horizontal stress averages 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 (corrected from Wang et al., 2017; Ulrich et al., 2018). The team therefore selected an area near the kISMET site for developing the Experiment 1 testbed – this site had a single lithology (the Ross member of the Poorman), and had a larger drift width and height that would accommodate the planned test facility.

2.2 Test Bed Design, Construction, and Characterization

The objective of the test bed for Experiment 1 was to create hydraulic fractures that would connect two parallel boreholes (Morris et al., 2018). This could be facilitated by designing the injection and production boreholes so that they would be parallel to the interpreted minimum principal stress (S_{hmin}) direction. Because the West Drift is oriented N33.5°E, these boreholes could be drilled obliquely to the drift and allow for a series of monitoring boreholes that could be drilled roughly parallel and perpendicular to the injection and production boreholes. The configuration of the monitoring boreholes was designed to be near to the hydraulic fractures that would be created by the experiment, so that the initiation and growth of these fractures could be detected by the instrumentation emplaced in these boreholes. The layout of these boreholes is depicted in Fig. 2.

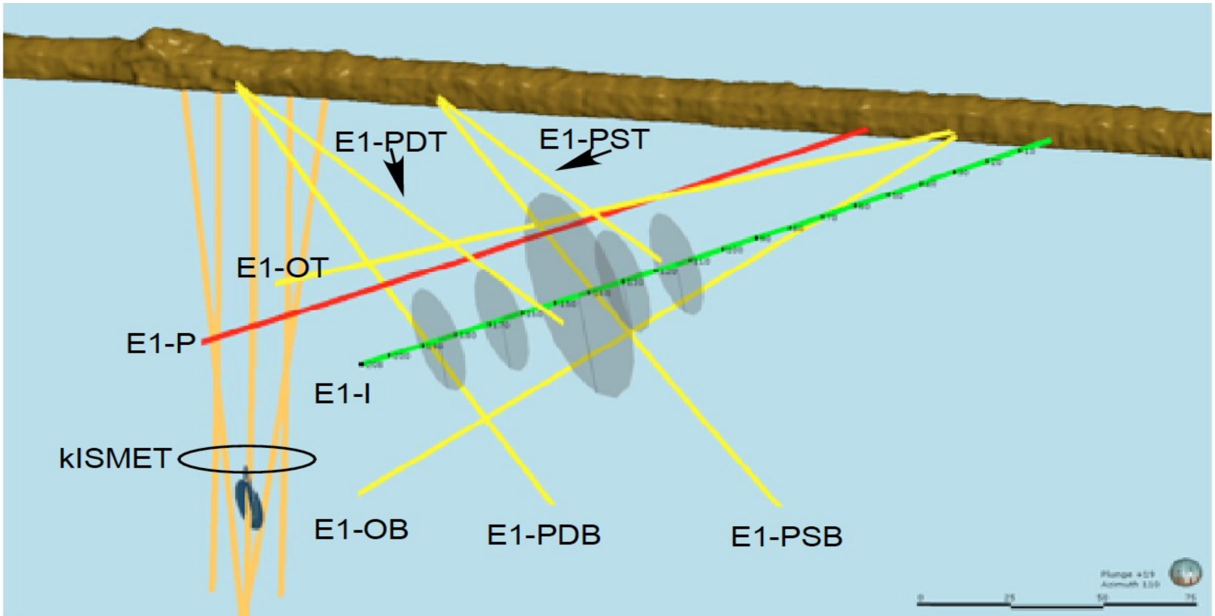


Figure 2: Layout of the boreholes for the Experiment 1 testbed on the 4850 level, with the brown feature at the top representing the West Drift (Kneafsey et al., 2019). E1-I (green) is the injection (stimulation) borehole (with the disks representing nominal locations for hydraulic fractures), E1-P (red) is the production borehole, the yellow lines represent the six monitoring boreholes (E1-OT, E1-OB, E1-PST, E1-PSB, E1-PDT and E1-PDB), and the orange lines represent the 5 boreholes from the kISMET experiment.

The boreholes were designed to be slightly downward-dipping from horizontal to facilitate wireline logging and packer conveyance. Agapito Associates, Inc. was contracted to drill and core these boreholes (HQ diameter) to a nominal depth of ~60 m each. After drilling the injection and production boreholes, a series of notches were scribed in the E1-I borehole at depths of approximately 40, 128, 142, 164, and 185 ft (12, 39, 43, 50, and 56 m, respectively) using a rig-deployed tool with carbide/polycrystalline-diamond cutters designed and built by Sandia National Laboratories to facilitate the initiation of hydraulic fractures perpendicular to the stimulation borehole axis (Morris et al., 2018). Over 450 m of core was recovered from the boreholes, and detailed description of the lithology, fractures, and veins was conducted. Additional characterization was carried out by the National Energy Technology Laboratory (NETL) on a suite of selected cores using a CT core scanner and a Geotek multi-sensor core logger to obtain measurements of density, magnetic susceptibility, compressional-wave velocity, and elemental abundances of Si, Ca, Fe, Al, K, Mg, S, Mn, Ti, and Cr. A comprehensive suite of wireline logs (optical and acoustic televiewer, full-waveform sonic, short and long electrical resistivity, and fluid temperature/conductivity) was run to provide detailed characterization of the rock properties and location and orientation of natural fractures within the boreholes. Based on previous hydrologic observations at SURF (Stetler, 2015), water-conductive fractures were expected to be sparse. Hydrologic characterization of the test bed was initiated, however, following observations of cross-flow during the drilling of the Collab boreholes. The hydrologic observations supported development of a deterministic discrete fracture network model containing several hydraulically-conductive fractures. While most of the identified fractures lacked natural (i.e., "ambient") hydraulic flow contribution, the presence of these fractures was likely to influence hydraulic fracture growth and flow testing within the test bed. Chemical and microbiological characterization of one of the flowing boreholes was also performed.

A comprehensive set of geophysical monitoring instrumentation was installed in each of the monitoring boreholes (Fig. 3). Prior to stimulation, seismic tomography surveys were conducted to develop 3-D seismic velocity models of the test bed. The electrical resistance tomography (ERT) and continuous active source seismic monitoring (CASSM) systems were also used to collect baseline data for the test bed. Additional details on the pre-stimulation site characterization can be found in Kneafsey et al. (2019).

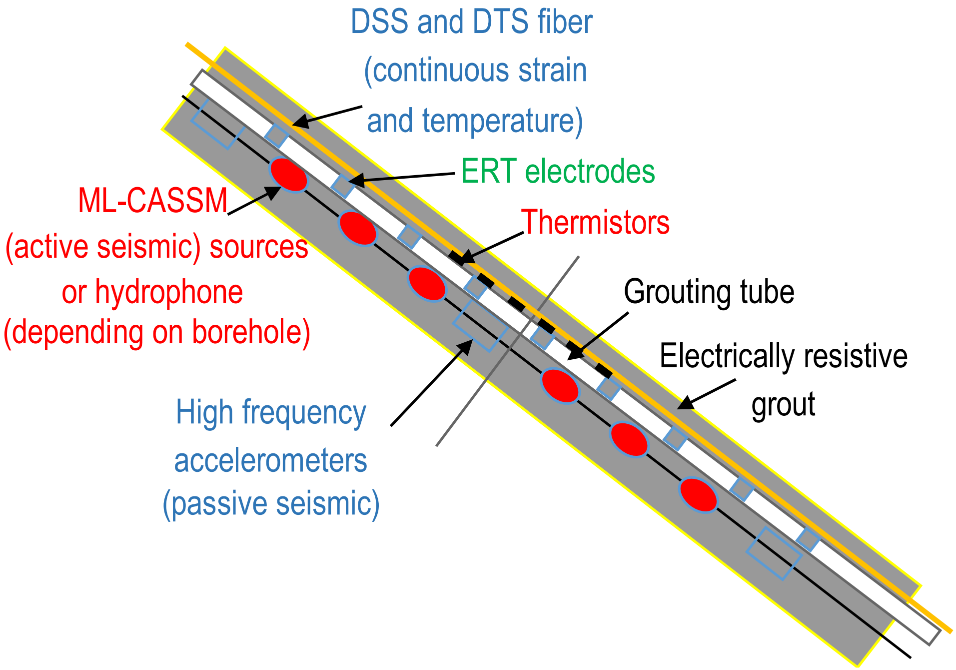


Figure 3: Schematic depiction of instrumentation of monitoring boreholes, permitting continuous measurement of temperature, seismicity, and electrical conductivity within the test bed. The sensors were grouted in place to create better coupling with the rock mass and to forestall fluid flow out the borehole (however, in many cases, fluid flow through the grouted boreholes occurred).

2.3 Earth Model

To facilitate integration and interpretation of these data, the EGS Collab team developed a 3-D earth model using Leapfrog software (Neupane et al., 2019). Data from both the pre-stimulation characterization and stimulation and flow testing phases of the project have been imported into this model. One of the key components is a discrete fracture network (DFN) model, which is used to evaluate how hydraulic fractures may interact with the natural fracture network. The DFN model was deterministically developed using observations of open fractures identified in core and boreholes, weep zones observed in the drift, cross flow detected between boreholes, and fluid entry points identified using a downhole video camera. Visualization of the DFN model was facilitated through the use of Leapfrog as well as Golder Associate's FracMan software (Fig. 4).

2.4 Site Characterization on the 4100 level

The EGS Collab team has initiated the establishment of a new testbed to conduct a second suite of stimulation and flow experiments, with a focus on shear stimulation (Experiment 2). As part of this effort, a number of potential sites were evaluated (Dobson et al., 2018). Key criteria include: 1) a test bed with well characterized stress state and a well described fracture network; 2) the presence of multiple sets of natural fractures of appropriate length and orientation so that they are suitable for shear stimulation; 3) low likelihood of leak-off through intersection with other permeable features or in the drift; and, 4) simple site geology (low heterogeneity) to facilitate interpretation of geophysical monitoring results. Based on an evaluation of several candidate sites, the battery alcove location on the 4100 level was selected for more detailed characterization, consisting of mapping of fractures on the drift walls, the drilling of a 50 m vertical borehole (TV4100) and a 10 m sub-horizontal borehole (TH4100), detailed core descriptions, temperature, conductivity, full waveform sonic, and optical and acoustic televiewer logging of the boreholes. The horizontal borehole and most of the vertical borehole encountered mostly the Ross Amphibolite member of the Yates Formation; intervals of Tertiary rhyolite were also intersected by the vertical borehole. A series of 10 hydrofracture stress measurements were conducted in the vertical borehole – the orientation of the minimum horizontal stress varies based on the borehole interval, but appears to be similar in trend to that obtained in the kISMET experiment on the 4850 level (Fig. 5). Three flowing fractures were identified in the vertical borehole – two of these were steeply dipping fractures in the rhyolite, and one was an open fracture in the lower part of the cased section of the borehole. Additional characterization of optimally-oriented sealed fractures within the vertical borehole using the SIMFIP tool is planned to determine if they can be shear stimulated, a requisite for Experiment 2.

3. HYDRAULIC FRACTURE EXPERIMENTS

3.1 Hydraulic Stimulations

For Experiment 1, a number of zones within the injection well (E1-I) were selected as candidates for hydraulic stimulation based on their position within the borehole and the paucity of natural fractures in the immediate vicinity. Stimulation of selected zones was conducted using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool, which uses straddle packers together with a deformable cage that can monitor real-time 3D mechanical deformation and associated pressure variations due to water injection (e.g., Guglielmi et al., 2014). The stimulation system uses multiple injection pumps that provide a range of flow rates, pressures, and precision control choices (Kneafsey et al., 2019). Each hydraulic stimulation was planned to have three sequences: an initial 1.5 m radius penny-shaped fracture, an extension to a 5 m radius fracture, and then further extension so that the fracture would intersect the production borehole located 10 m from the injection well. The first hydraulic fracture stimulation was conducted at the 142’ notch (43.3 m from the borehole collar), but initial observations suggested that the created hydraulic fracture intersected a nearby natural fracture, so the test was halted. The SIMFIP packer system was then moved to the 164’ notch (50.0 m from the borehole collar), where hydraulic creation and stimulation of a fracture was carried out in three phases (Fig. 6). For the initial step, 2.1 L of water was injected to create a ~1.5 m radius fracture, with a propagation pressure of 25.43 MPa and an instantaneous shut-in pressure of 25.37 psi. The second step (to create a 5 m radius fracture) had an injection volume of 23.5 L of water, with slightly higher propagation and instantaneous shut-in pressures (25.95 and 25.82 MPa, respectively). The final phase of this stimulation (to have the hydraulic fracture intersect the production well) had an injection volume of 80.6 L, with propagation and instantaneous shut-in pressures of 26.88 and 25.31 MPa, respectively. This hydraulic fracture did intersect the E1-P well as planned, but also intersected one of the monitoring wells (E1-OT) that is located between E1-I and E1-P, as indicated by seismic sensors, a temperature increase detected by the DTS, and eventual water flow out of the grouted monitoring borehole. Stimulation was also conducted at the 128’ notch (39.0 m from the borehole collar); flow from this stimulation bypassed the top injection packer through fractures and resulted in a hydraulic fracture that connected to the E1-OT monitoring borehole, but did not extend to the E1-P borehole.

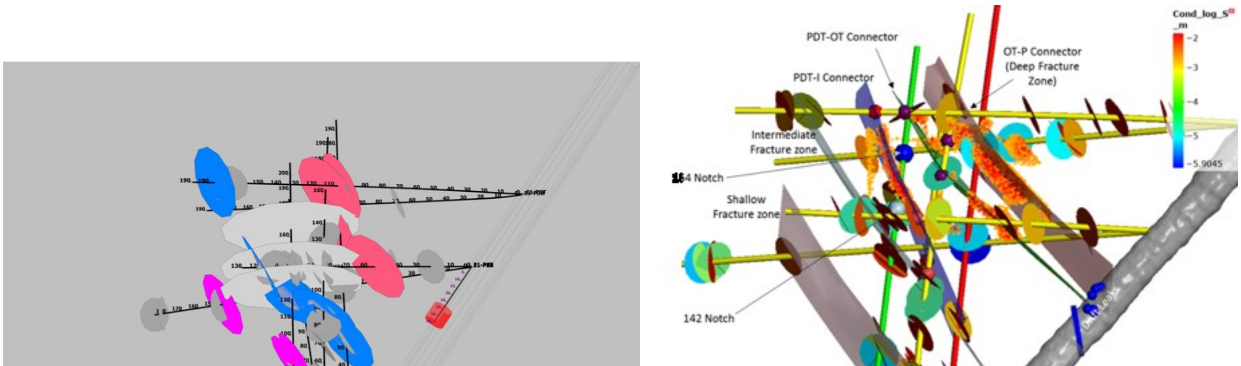


Figure 4: Left) Discrete fracture network model for Experiment 1 testbed displayed using FracMan, with different colored disks representing different fracture groups (Kneafsey et al., 2019). Right) Main fracture flow pathways depicted using Leapfrog, along with notch locations where hydraulic fractures were initiated in the stimulation well (E1-I) (Neupane et al., 2019).

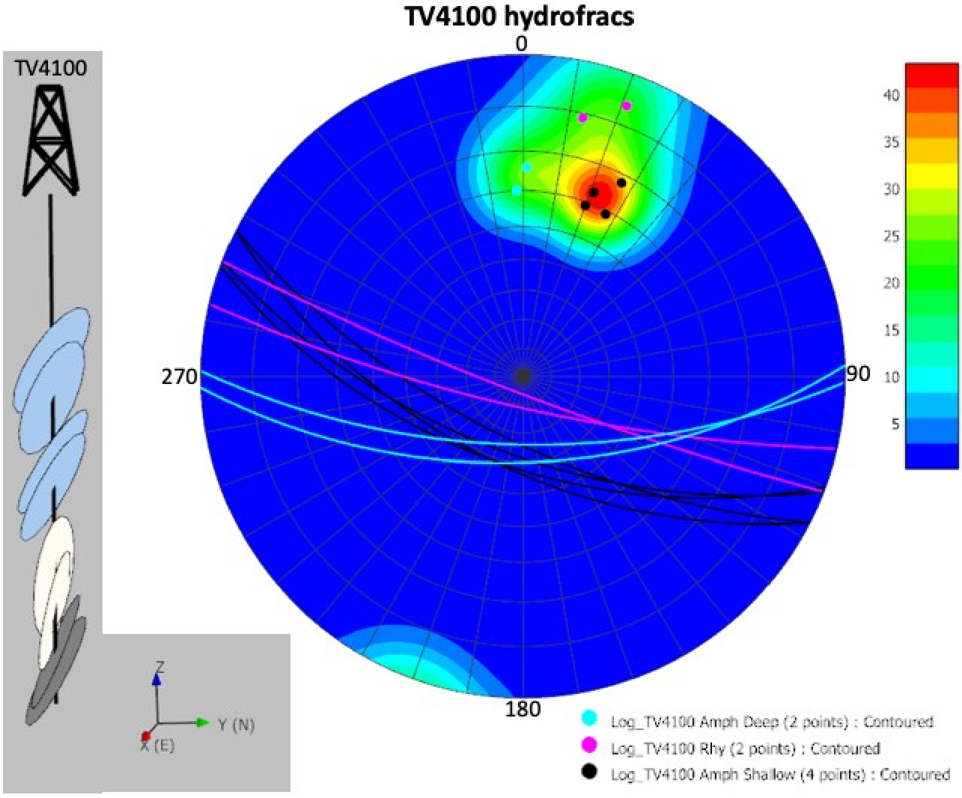


Figure 5: Orientations of the hydrofractures created in the TV4100 borehole. All results presented with respect to true north (magnetic north is 7.8° E of true north). Three distinct clusters of orientations were observed – one for the shallower set of hydrofractures in the Yates amphibolite, one for the two hydrofractures in the rhyolite, and one for the deeper set of hydrofractures in the Yates amphibolite. These features are interpreted to be oriented parallel to SH_{max}.

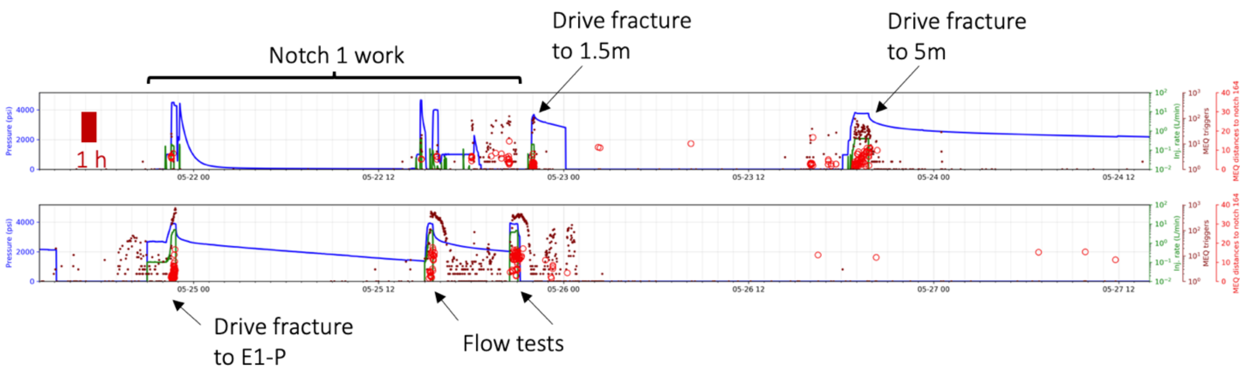


Figure 6: Stimulation of the 142' notch (Notch 1 work) and 164' notch (Drive fracture to 1.5 m, 5 m, and E1-P intervals and flow tests) with plot indicating injection pressure (blue) and rate (green), abundance of MEQ triggers per minute (brown), and the MEQ distance (m) to the stimulated notch (red circles). Some seismicity was associated with other activities in the mine (Schoenball et al., 2019).

3.2 Stimulation Monitoring

Multiple sensing devices were used to monitor each of the stimulations. Three of the primary methods that were employed were distributed temperature sensing (DTS), passive seismic monitoring, and ERT. Contrasts in temperature between the host rock and the injected fluids allowed for precise detection of the arrival and migration of fluids within the monitoring boreholes. Differences in chemical composition between the injected and formation waters resulted in changes in electrical conductivity when injected fluids arrived in the monitoring boreholes. The initiation and growth of the hydraulic fractures was also signaled by the temporal evolution of microseismicity (Fig. 7) within the test bed (Schoenball et al., 2019; Fu et al., 2019).

Other monitoring methods that provide important constraints on the stimulation activity include the SIMFIP tool, which determines the orientation and magnitude of fracture displacement in the borehole over time, and the CASSM system, which detects changes in seismic velocities that may be attributed to changes in the fracture network. Another monitoring method that was employed was a downhole camera that allowed for recording the exact location and nature of water inflow into the production borehole (Fig. 8). Measurements of distributed strain and acoustic sensing with fiber optic cable were also utilized.

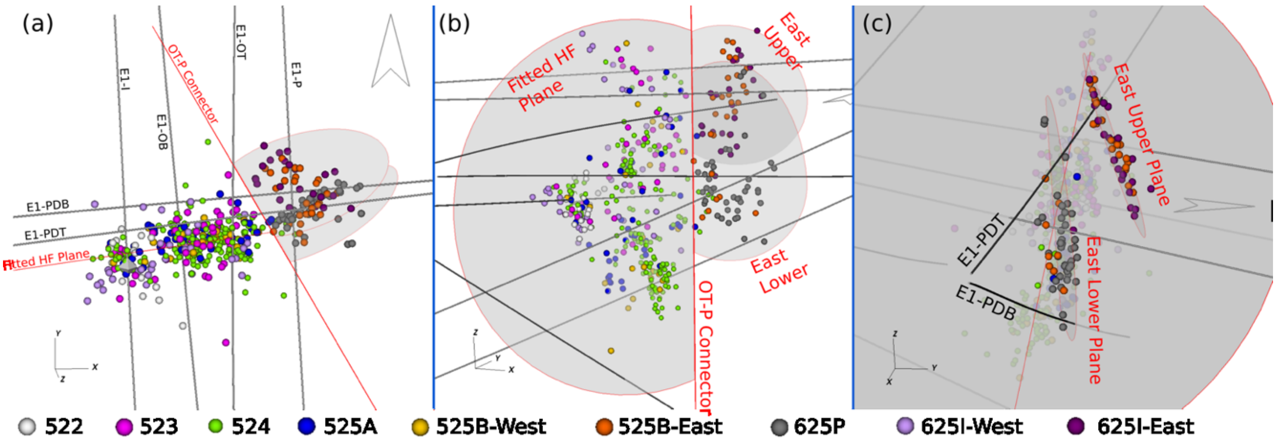


Figure 7: Microseismic response to the stimulation of the 164' notch (Fu et al., 2019). (a) plan view of the test bed; (b) side view along the OT-P connector plane; (c) side view from the east of the OT-P connector plane. 522 represents initial 1.5 m radius stimulation, 523 represents 5 m radius stimulation, and 524 represents the stimulation to the production borehole, with 525A, 525B, 625P, and 625I representing subsequent injections (numbers represent month and day of the injection – e.g., 522 indicates May 22). Note that the arrays of MEQs appear to highlight discrete fracture planes. The MEQs from a) and b) correlate with the stimulation data depicted in Figure 6.

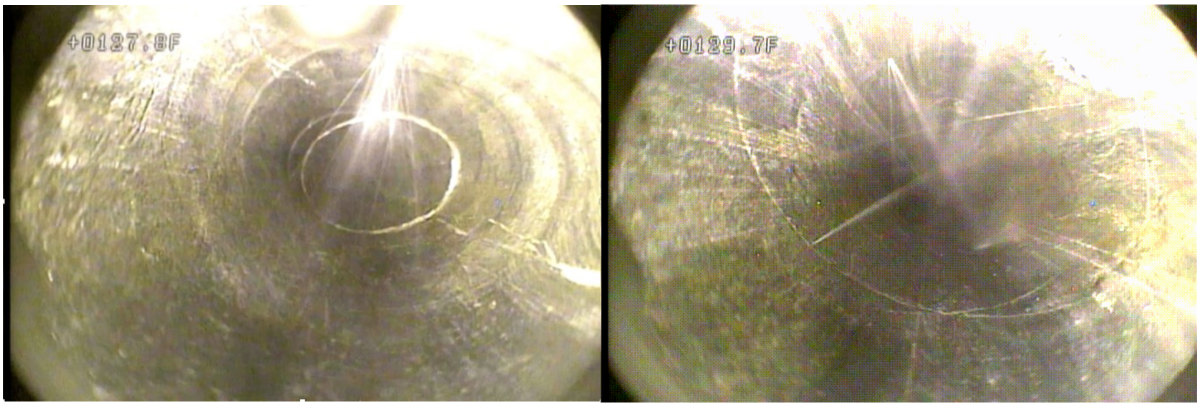


Figure 8: Water jets observed in the EI-P borehole using a downhole camera following injection into the E1-I borehole. Left) Jets located at a depth of 127.8 ft (39.0 m); Right) Jets located at a depth of 129.7 ft (39.5 m).

4. FLOW TESTS

4.1 Early Flow Testing

Following the creation of the hydraulic fractures, a series of flow tests of varying durations and flow rates have been conducted to better understand the flow pathways within the Experiment 1 test bed. The initial conceptual model for Experiment 1 was that hydraulic fractures would be created in the injection borehole that would create simple fracture pathways to the production borehole. However, the presence of open natural fractures that were intersected by the hydraulic fractures resulted in early termination of the growth of the hydraulic fractures (such as the case with the attempted stimulation of the 142' notch) or in the partial diversion of flow along these existing natural fractures, some of which discharged into the drift. An additional complicating factor to these tests was the development of flow pathways within many of the monitoring wells through the grout to the collar; a concerted effort was made by the team to seal some of these boreholes through the repeated injection of grout and epoxy so that a greater fraction of the flow would end up in the production borehole. Higher injection rate flow tests seemed to cause the most damage to these boreholes, so later flow tests were designed to be conducted at lower flow rates (typically 400 mL/min) to avoid causing damage to the test bed. Another issue confronting early flow tests was a fairly rapid increase in pressure, which often required a reduction in flow rate to stay below fracture propagation pressures. Some changes in the system's behavior were observed following interruptions in injection, cycling of different flow rates, injection of a biocide, and switching to deionized water injection, suggesting that there were near borehole effects as well as a dynamic flow system. Descriptions of these early flow tests (Fig. 9) are presented by Kneafsey et al. (2019) and Ingraham et al. (2019).

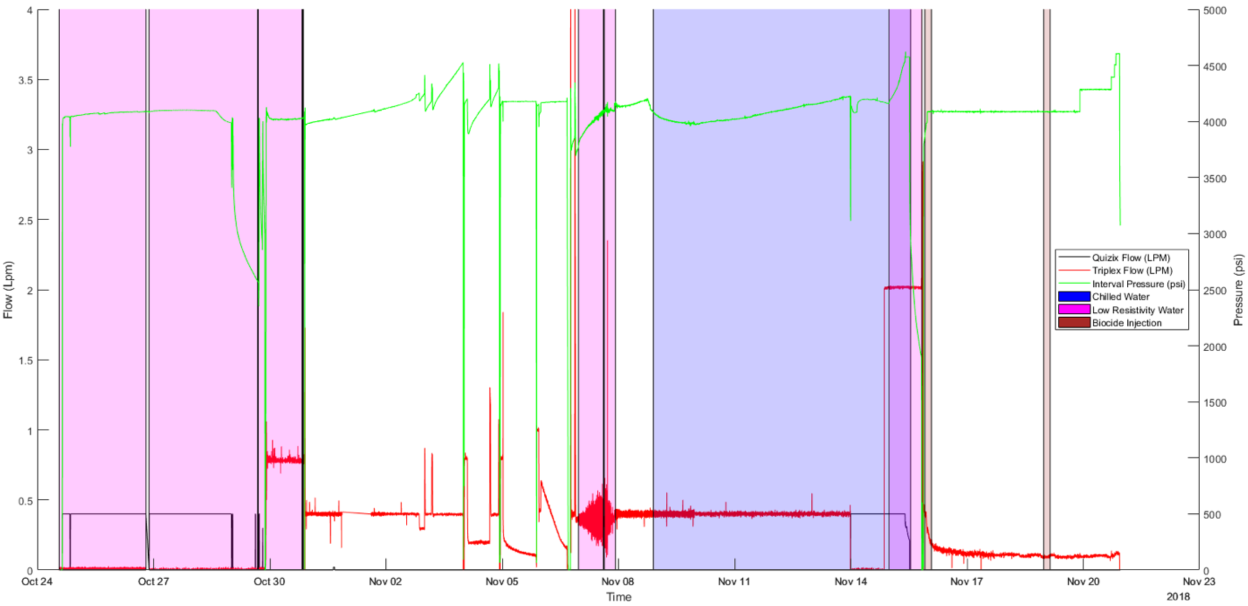
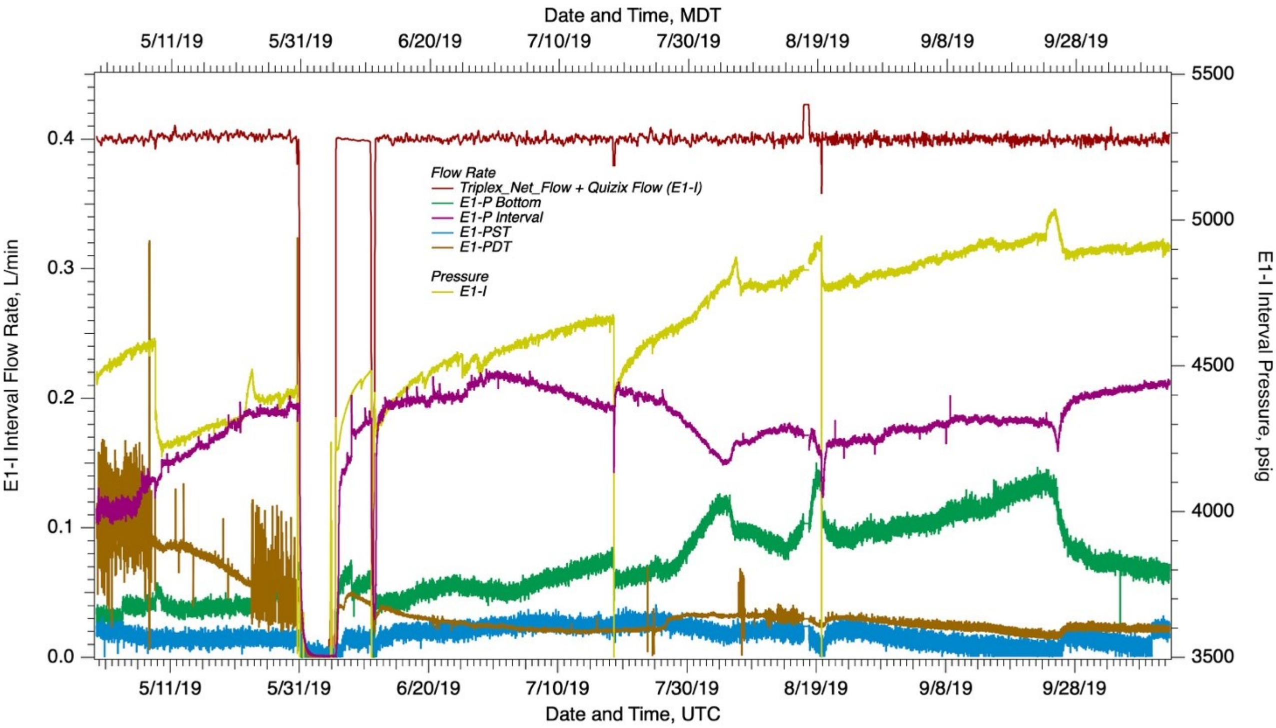


Figure 9: Pressure and flow curves for long-term injection test conducted using the 164' notch during October and November of 2018 (Ingraham et al., 2019). Shaded regions reflect different sources of injection water (pink = deionized water, blue = water below 20°C, and brown = water with biocide).

4.2 Long-Term Chilled Water Flow Test

Flow behavior for the 164' notch appeared to have stabilized in the spring of 2019, when higher fluid recovery rates (~85%) and smaller pressure changes with continued injection were observed. A long-term flow test with an injection flow rate of ~400 mL/m was initiated in this zone using chilled water (~12°C when injected into the packer interval for the 164' notch in E1-I) – the background rock temperature is as high as 32°C in the deeper part of the testbed and cooler near the drift. The primary objective of this flow test was to provide detailed field observations that can constrain coupled process models that will evaluate the heat exchange occurring between the rock mass and injected fluid flowing within the fracture network. Observations from the first five months of this test (Fig. 10) reveal that the produced fluids exhibit complex behaviors, with the temperature from one interval of the production well increasing constantly and that from another interval having experienced a mild decrease. The observed thermal response likely reflects the combined effects of the background temperature gradient, thermal breakthrough, and the Joule-Thomson effect.



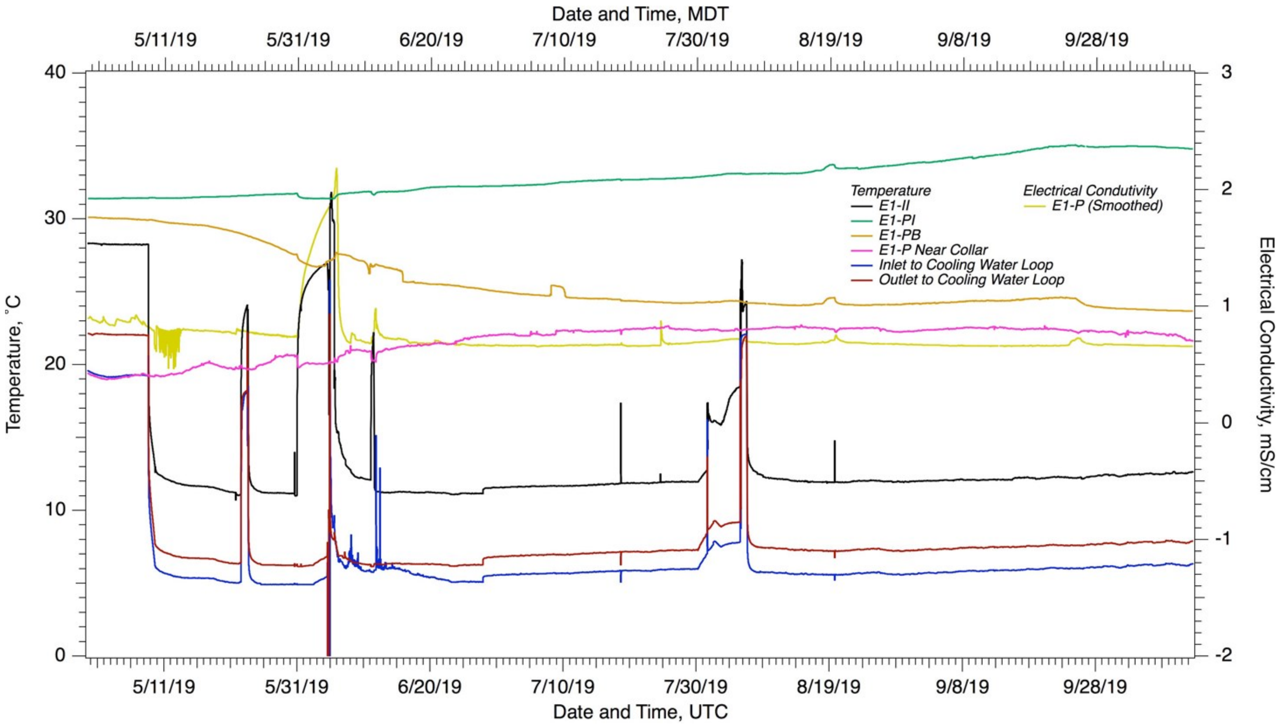


Figure 10: Preliminary results of long-term chilled water flow test (April-October 2019). Upper plot depicts injection rates into the 164’ notch in E1-I, outflow rates for E1-P, E1-PST, and E1-PDT, and the injection interval pressure. E1-PI is the interval is the zone between the straddle packers in the production well, E1-PB is the zone below the lower packer, and E1-P near collar is the water collected at the drift wall. The lower plot depicts temperature variations in injection and outflow fluid temperatures over time, along with changes in electrical conductivity within E1-P. Operational issues with pumps and one of the chiller units are linked to some of the abrupt changes seen in the plots.

4.3 Tracer Tests

The flow tests have often been accompanied by the injection of conservative and sorbing chemical tracers (e.g., Hawkins et al., 2018; Mattson et al., 2019) to track the rate and relative proportion of tracer recovery within the production borehole as well as several of the monitoring boreholes where fluid flow from the well through the grout was observed to occur. The suite of tracers that have been utilized thus far for Experiment 1 includes C-Dots fluorescein nanoparticles (Hawkins et al., 2017), DNA, fluorescein, rhodamine-B, sodium chloride, lithium bromide and cesium iodide, as well as several incidental tracers from using different injectate water (mine water, softened mine water, and deionized water). An example of breakthrough curves for one of these tracer tests (with results adjusted to account for the residence time in the boreholes prior to sampling in the drift) are depicted in Fig. 11.

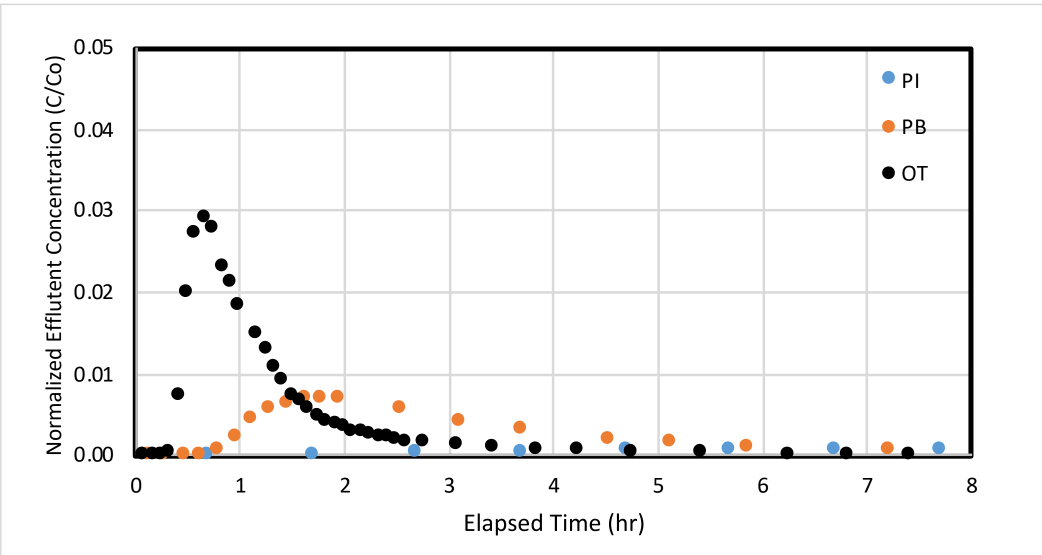


Figure 11: Breakthrough curves for C-Dot tracer injected into the 164’ notch of the E1-I well on Nov. 14, 2018 (Kneafsey et al., 2019). PI – packer interval of the production well; PB – zone below the packer in the production well; OT – water collected from the leaking E1-OT monitoring borehole. The E1-P well is located 10 m away from the E1-I well (see well schematic in Fig. 2).

5. NUMERICAL MODELING

One of the main objectives of the EGS Collab project is to collect comprehensive field observations that can be used to constrain and validate coupled process models. Modeling efforts for this project include both predictive models used to help design field experiments as well as numerical simulations that were conducted using field data to assist with the interpretation of the stimulation and flow experiments. An overview of these modeling efforts is reported by White et al. (2019); these efforts are ongoing.

5.1 Simulations Supporting Experiment Design

Numerous modeling efforts were involved in the design of the experimental test bed (the orientation and spacing of the boreholes and deployment of monitoring sensors) as well as in the design of actual stimulation and flow experiments. These efforts included prediction of the orientation and growth of stimulated hydraulic fracture as impacted by drift excavation and thermal stresses (Fig. 12), the optimal location of seismic sensors for monitoring fracture stimulation (Chen et al., 2019), and the impact of cutting notches to develop stimulated fractures that will propagate perpendicular to the borehole axis in the direction of S_{Hmax}. Numerical simulations were also used to help design flow and tracer tests, helping to determine optimal operational parameters (such as flow rates, pressures, injected tracer concentrations) for these experiments.

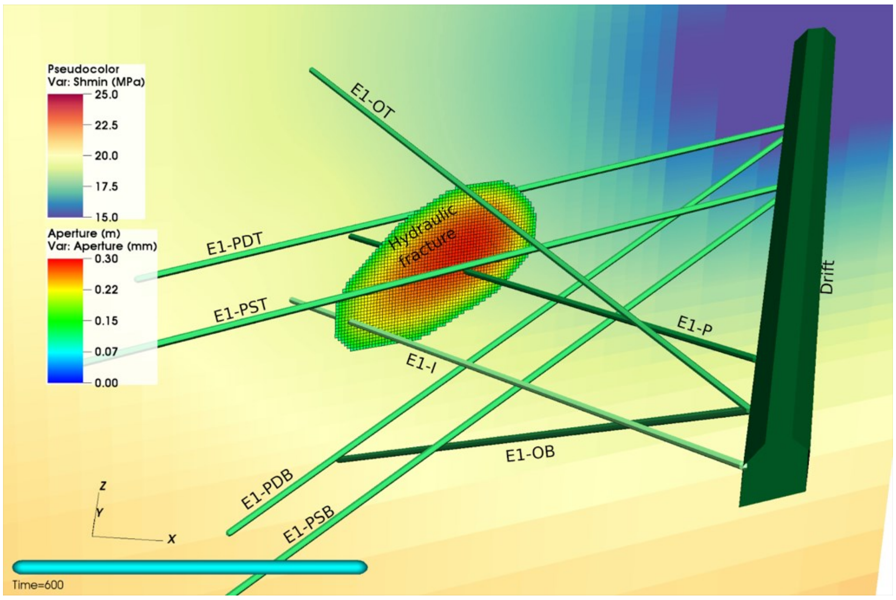


Figure 12: Simulation using GEOS of fracture extent and aperture distribution after 6 minutes of injection at 0.1 L/s into E1-I under the strong influence of stress perturbation caused by the drift. Shown in the background is the magnitude of the minimum principal stress in the rock body on a planar "slice" that is parallel to and 5 m away from the expected fracture plane.

5.2 Simulations for Interpretation of Experimental Results

A focus of the modeling team has been on using coupled process models to help interpret the results of the stimulation and flow field experiments. One of the challenges associated with developing these models is that the fracture system is complex (Fig. 4) and responds dynamically to injection. Initial simulations of tracer returns conducted using a Monte Carlo approach (Wu et al., 2019) suggest that the models that best match the observations require fractures with heterogeneous apertures (Fig. 13). Additional modeling is currently being conducted to evaluate the changes in temperature observed in the flowing boreholes over time during the long-term chilled water injection test. More complete integration of monitoring data into these models should lead to more robust constraints on the locations and flow properties of permeable fractures within the Experiment 1 test bed.

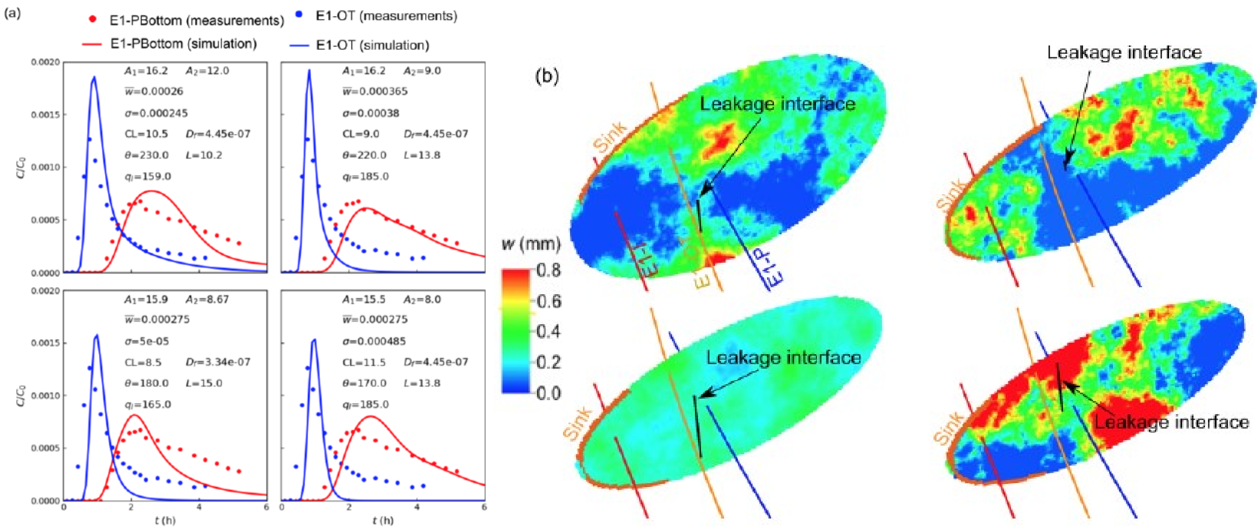


Figure 13: Modeling results of tracer transport in the hydraulic fracture with a heterogeneous aperture (Wu et al., 2019). Left) Comparison of observed (dots) and modeled (lines) breakthrough curves at E1-P bottom and E1-OT for four different realizations. Right) Aperture distribution for the different realizations.

6. PRELIMINARY OBSERVATIONS AND FUTURE PLANS

Using the eight-borehole testbed developed for Experiment 1, the EGS Collab team has successfully conducted a series of hydraulic stimulation and flow tests. The presence of conductive natural fractures within the testbed has complicated efforts to grow hydraulic fractures, and has also resulted in more complex flow paths, making interpretation of flow test results more challenging. Several important observations were obtained from the experiments and simulations that have been conducted to date. These include:

1. The stimulated hydraulic fractures do not form penny-shaped cracks, but instead are asymmetric, likely based on local stress heterogeneities. This behavior was successfully predicted in pre-stimulation modeling.

2. The hydraulic fracture that was created at the 164' notch in the E1-I borehole ended up intersecting the EI-P borehole in the predicted depth interval based on simulations using the stress regime that was previously measured in the nearby kISMET boreholes. However, the hydraulic fracture that was initiated at the 142' notch intersected a significant natural fracture prior to reaching the production, impeding its growth.

3. The development of a discrete fracture model aided significantly in interpreting the results of the flow and tracer tests. Numerous types of observations obtained from cores, borehole imaging, hydraulic testing, DTS, CASSM, ERT, passive seismic, and also the flow and tracer tests are used in the continuous development of this model.

4. The Experiment 1 test bed is a dynamic system – continued injection changes the flow response of the system. Higher flow rates (and pressures) tend to perturb the system more.

5. Many of the grouted monitoring boreholes inadvertently ended up being flow pathways. While this provided confirmation of fracture connections prior to reaching the production borehole, it also complicated subsequent flow and tracer tests.

6. The monitoring system generates large volumes of data (terabytes per week). Our team developed edge data processing methods to facilitate initial real-time data analysis, and subsequent data transmission to the team (Weers and Huggins, 2019).

7. Data integration and interpretation has been facilitated by an earth model representing rock and fracture properties of the first testbed in 3-D (Neupane et al., 2019).

8. This project has relied on active collaboration of a strong multidisciplinary team that has been able to conduct a wide range of field characterization, monitoring, fracture generation, fluid flow, and thermal flow test experiments along with associated coupled process modeling. Weekly field and modeling calls, along with a cloud-based data collaboration site, have resulted in excellent communication between the various team members. Data is ultimately uploaded to the U.S. DOE's Geothermal Data Repository (Weers and Huggins, 2019) to facilitate sharing results with the scientific community.

Additional modeling work on the results of Experiment 1 is continuing. The team is currently identifying an appropriate test bed to conduct shear stimulation of natural fractures, the primary objective of Experiment 2 of this project (Singh et al., 2019). Two boreholes were drilled on the 4100 level (1250 m below the ground surface) in the Yates amphibolite to characterize natural fractures and make stress measurements at this location. The characterization effort, in conjunction with the lessons learned from Experiment 1, will shape the design and approach of Experiment 2. The evolutionary suite of EGS Collab meso-scale models, validated with robust field experimentation, will provide critical insights to the methodology and implementation of the full-scale FORGE initiative and ultimately towards commercial deployment of industrial EGS.

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