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The EGS Collab Project: Status and Accomplishments

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ABSTRACT

The EGS Collab project, supported by the US Department of Energy, is addressing challenges in implementing enhanced geothermal systems (EGS). This includes improving understanding of the stimulation of crystalline rock to create appropriate flow pathways, and the ability to effectively simulate both the stimulation and the flow and transport processes in the resulting fracture network. The project is performing intesively monitored rock stimulation and flow tests at the 10-m scale in an underground research laboratory. Data and observations from the field test are compared to simulations to understand processes and to build confidence in numerical modeling of the processes.

In Experiment 1, we examined hydraulic fracturing an underground test bed at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, at a depth of approximately 1.5 km. We drilled eight sub-horizontal boreholes in a well-characterized phyllite. Six of the boreholes were instrumented with many sensor types to allow careful monitoring of stimulation events and flow tests, and the other two boreholes were used for water injection and production. We performed a number of stimulations and flow tests in the testbed. Our monitoring systems allowed detailed observations and collection of numerous data sets of processes occurring during stimulation and during dynamic flow tests. Long-term ambient temperature and chilled water flow tests were performed in addition to many tracer tests to examine system behavior. Data were rapidly analyzed, allowing adaptive control of the tests. Numerical simulation was used to answer key experimental design questions, to forecast fracture propagation trajectories and extents, and to analyze and evaluate results. Many simulations were performed in near-real-time in conjunction with the field experiments, with more detailed process study simulations performed on a longer timeframe.

Experiment 2 will examine hydraulic shearing in a test bed being built at the SURF at a depth of about 1.25 km in amphibolite under a different set of stress and fracture conditions than Experiment 1. Five sets of fracture orientations were considered in design, and three orientations seem to be consistently observed.

1. Introduction

Enhanced (or engineered) geothermal systems (EGS) could help support the energy security of the United States by significantly expanding the potential for domestic geothermal energy production. EGS resource estimates exceed 500 GWe for the western US, [*Williams et al.*, 2008], with some estimates up to an order of magnitude larger for the entire country [*Augustine*, 2016]. Implementing EGS requires improving (1) the understanding and efficacy of stimulation techniques to allow optimal communication among multiple wells, (2) imaging and monitoring techniques for permeability enhancement and evolution, as well as associated seismicity, (3) technologies for zonal isolation for multistage stimulations under elevated temperatures, (4) technologies to isolate zones for controlling fast flow paths and control early thermal breakthrough, and (5) scientifically-based long-term EGS reservoir sustainability and management techniques.

We are working to refine our understanding of rock mass response to stimulation in deep crystalline rock and its effect on heat exchange with circulating fluids. By performing stimulation and flow experiments on a 10-m spatial scale under stresses relevant to EGS, we are supporting validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches. In addition, we are testing and improving conventional and novel field monitoring tools. One goal is increased understanding and predictive capability of permeability enhancement and evolution in crystalline rock, including how to create sustained and distributed permeability for heat extraction from a reservoir by generating new fractures that complement existing fractures. The project has planned three multi-test experiments to increase understanding of hydraulic fracturing in Experiment 1, shear stimulation in Experiment 2, and other stimulation methods in Experiment 3. At the time of writing, the Experiment 1 field tests have been completed and the construction of the Experiment 2 testbed is underway. Modeling supports experiment design, control, and post-test analysis and comparison to data. Comparing model and measurement results from tests builds confidence in and allows improvement of the array of modeling and monitoring tools in use.

2.0 Status

2.1 Experiment 1

Experiment 1 [*Kneafsey et al.*, 2020] was performed on the 4850 (feet deep, ~1.5 km) level at the Sanford Underground Research Facility (SURF, Figure 1) in Lead, South Dakota [*Heise*, 2015]. The fieldwork for this experiment is complete and data analysis continues. This experiment was intended to establish a fracture network that connects an injection and a production well using hydraulic fracturing [*Morris et al.*, 2018b]. The Experiment 1 testbed is shown in Figure 2. All boreholes were subhorizontal, nominally 60 meters long, and were continuously cored. The injection and production boreholes (green and red lines in Figure 2) were drilled approximately parallel to the minimum principal stress direction. Ideal penny-shaped hydraulic fractures would be expected to propagate orthogonally to the injection well in general, however in the vicinity of the well tortuosity effects could occur. The kISMET (permeability (k) and Induced Seismicity Management for Energy Technologies) project wells and characterizations in adjacent rock shown in the orange boreholes [*Oldenburg et al.*, 2017; *Wang et al.*, 2017] provided information on the stresses and their orientations. Six monitoring wells (yellow in Figure 2) contained grouted-in instrumentation. In general, boreholes were characterized using optical and acoustic televiewers, full waveform sonic, electrical resistivity, natural gamma, and temperature/conductivity logs as well as from descriptions and analyses of the recovered core.

The Experiment 1 test block characterization used seismic tomography, electrical resistance tomography (ERT), and extended hydrologic characterization including tracer tests (see Kneafsey et al. [2020]). Passive seismic monitoring, continuous active source seismic monitoring (CASSM), dynamic ERT imaging using high-contrast fluids, acoustic emissions, and distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), and strain (DSS) changes were used to monitor stimulation and flow. Many tracer tests were performed to monitor flow and stimulation tests. Fracture aperture strain monitoring was performed using the Step-rate Injection Method for

Fracture In-situ Properties (SIMFIP) tool (see Guglielmi et al., 2021). Laboratory investigations provided additional process understanding (See *Kneafsey et al.* [2019b]). Data collected and analyzed are stored on a data storage collaboration space (EGS Collab Open EI site) and later moved to DOE's Geothermal Data Repository (GDR) where they are publicly available [*Weers et al.*, 2020; *Weers and Huggins*, 2019; *Weers et al.*, 2018]. Journal and conference articles and reports describing individual methods, test results, and simulations can be found on the EGS Collab wiki[b], Google Scholar[c] under the author name: "EGS Collab" and the GDR[d]. Large data sets, for example microseismic data, are available through the authors.

2.1.1 Stimulations

Stimulations and hydraulic characterizations were performed from May to December 2018 (see Table 1.) [*White et al.*, 2019]. Details of the stimulations and methods are presented in *Kneafsey et al.* [2019a]; *White et al.* [2019]. In short, notches were carved in the injection borehole at locations of interest. Stimulations were performed stepwise to create a 1.5 m radius fracture (ideal), a 5 m radius fracture (ideal) and a fracture exceeding 10 m to intersect the production well. The well was typically shut in after each step overnight and pressure data were collected.

Hydraulic Stimulation #1 at 142' Notch - 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.

Hydraulic Stimulation #2 at 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.

Hydraulic Stimulation #3 at 128' Notch - 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

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

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

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

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.

Hydraulic Stimulation #4 at 142' Notch - 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. 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.

Data from Experiment 1 stimulation activities are available on the GDR [*Knox et al. 2020*].

Table 1. Experiment 1 Stimulations

Event	Duration
Hydraulic Stimulation #1 at 142' Notch	May 21, 2018 - May 22, 2018
Hydraulic Stimulation #2 at 164' Notch	May 22, 2018 - May 24, 2018
Hydraulic Characterization #1 at 164' Notch	Jun. 14, 2018 - Jul. 12, 2018
Hydraulic Stimulation #3 at 128' Notch	Jul. 18, 2018 - Jul. 20, 2018
Hydraulic Characterization #2 at 164' Notch	Oct. 24, 2018 - Nov. 20, 2018
Hydraulic Stimulation #4 at 142' Notch	Dec. 7, 2018 - Dec. 20, 2018
Hydraulic Characterization #3 at 142' Notch	Dec. 21, 2018 - Dec. 21, 2018

2.1.2 Flow tests

Both ambient temperature and chilled water flow tests have been performed [*Kneafsey et al.*, 2020]. Briefly, long-term ambient temperature and chilled water flow tests were performed for about 10 months. In these tests, water was 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 (i.e., the fractures are not growing). 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 reaching near full recovery, however recovery was from multiple locations (e.g., the grouted monitoring wells as well as the production well). 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 differs 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 various flow paths.

Injection pressure behavior - First, the injection pressure required to maintain the selected flow rate was significantly higher than the ISIP (ISIP on the order of 25.5 MPa (3700 psi) vs. ~ injection pressure 34.5 MPa (5,000 psi)), and this pressure always continued to rise under continuous flow conditions. Shutdowns, even brief shutdowns from restarting the pump, resulted in a lower injection pressure for the same injection rate. The pressure would again increase over time until another shutdown or stimulus was 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 pore space 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”. Numerical models have been able to show the pressure trend assuming the poroelastic explanation, however some biofouling and precipitate fouling may be occurring concurrently.

Chilled water injection - When chilled water was initially injected, 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 continued pressure increase. When warm water was injected, the reverse effect occurred. The injection pressure increased as the near-borehole fracture apertures were reduced by expanding rock.

Dynamic testbed - At times without applying a stimulus to 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. This provides an example of the dynamic nature of the system. Cross correlation of data sets may shed more light on this.

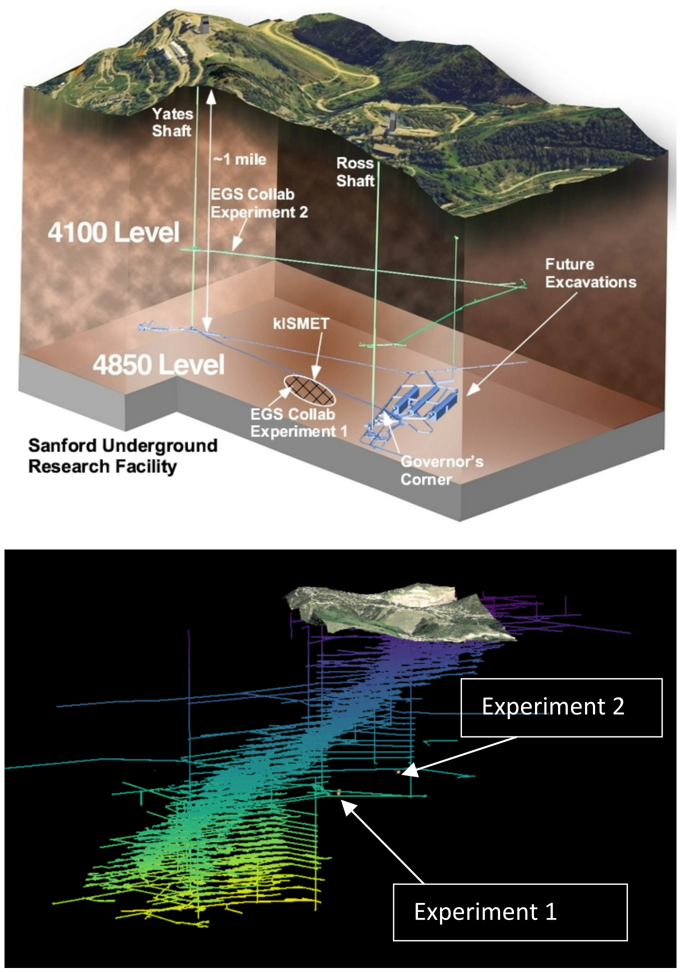

Figure 1: Top - Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, the location of the kISMET experiment, the 4100 level and the locations of Experiments 1 and 2. Bottom – spatial relationship between EGS Collab testbeds and former mine workings.

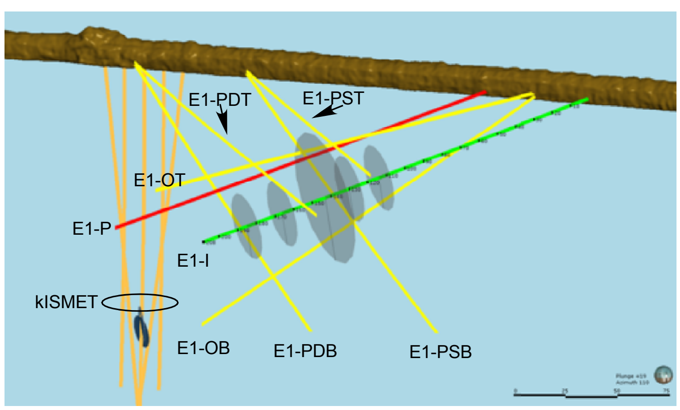

Figure 2: Experiment 1 schematic along the West Drift on the 4850 level of SURF. Green line - stimulation (injection) well (E1-I), red line - production well (E1-P), yellow lines - monitoring wells, and orange lines - kISMET wells. The two monitoring wells originating between E1-I and E1-P – rightmost intersection with the drift (brown) 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. E1-I and E1-P are approximately parallel to Shmin and the gray disks indicate nominal hydraulic fractures.

2.2 Experiment 2

Experiment 2 is intended to investigate shear stimulation. The testbed is being constructed on the 4100 (foot depth, ~1.25 km) level at SURF. The target rock formation is the Yates amphibolite. The subsurface stress conditions differ from those on the 4850 level in that there is lower vertical stress and a stress heterogeneity related to an intruded rhyolite layer present [*Ingraham et al.*, 2020]. Pre-test characterization of the 4100 level has included observed fracture and feature mapping, the drilling and logging of a 10 m horizontal borehole and a 50 m vertical borehole, and stress tests. The vertical borehole identified and penetrated a thick (~11 m) rhyolite layer. Eighteen stress tests have been performed in the vertical borehole and eight of these have used the SIMFIP tool to quantify displacement during testing. Instantaneous shut-in pressures (ISIP) indicated that the minimum principal stress can be grouped into 3 zones (Figure 3). In the amphibolite below the rhyolite, ISIP values are around 27.6 MPa (4000 psi). ISIP values in the rhyolite vary around 18.6 MPa (2700 psi). In the upper amphibolite ISIP values vary around 21.4 MPa (3100 psi). Because of this stress heterogeneity, the Experiment 2 test bed is designed to be entirely *above* this rhyolite layer. Cores have been examined and photographed, and distributed for initial laboratory tests. These data feed into concepts used in the design of the Experiment 2 test bed, which consists of nine boreholes to be used for injection, production, and monitoring. Drilling is underway at the time of this writing.

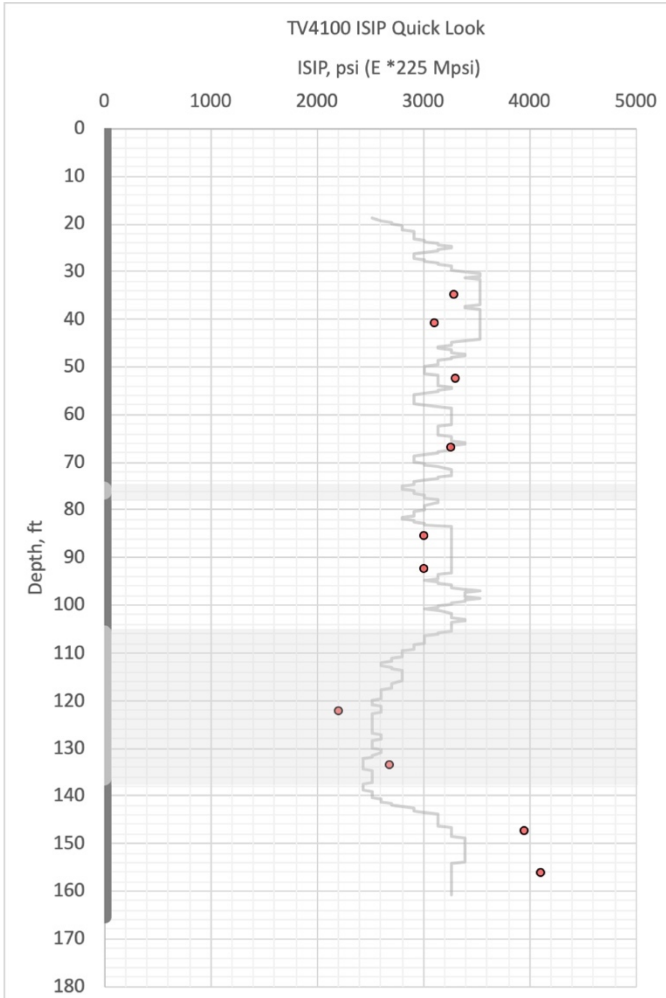

Figure 3. Instantaneous shut-in pressures (red dots) for tests at 10 locations in the 50 m vertical borehole on the 4100 level (no SIMFIP). The grey line is the dynamic Young's modulus from full waveform sonic data, and the shaded bar on the left indicates the rock type encountered (dark = amphibolite, light = rhyolite). Note the high ISIP below the rhyolite, low ISIP in the rhyolite, and moderate relative consistent ISIP above the rhyolite in the upper amphibolite section.

The primary objective of Experiment 2 is to achieve shear stimulation. Hence, a major design consideration is to identify features that are suitably oriented for shear reactivation. It is the combination of stress conditions and fracture orientations that lead to propensity for slip. The stress state is uncertain, but our design was based upon the assumption of $\sigma_{hmin} = 18.3$ MPa, $\sigma_{Hmax} = 37.3$ MPa, and $\sigma_V = 36$ MPa, with σ_{hmin} oriented 24° east of north and dipping 28° below horizontal. The pore pressure, P_p, is estimated to be 4.23 MPa.

3.0 Accomplishments

In addition to building and instrumenting test sites [*Dobson et al.*, 2018; *Knox et al.*, 2017; *Morris et al.*, 2018a; *Singh et al.*, 2019], and performing stimulations, flow test, chilled flow tests, and tracer tests, we have made progress in a number of areas including 1) data processing, annotation, and integration; 2) processing seismic data, 3) connecting geophysics, fractures, and flow systems, and 4) modeling fractured flow systems.

3.1 Data processing, annotation, and integration

The EGS Collab project has collected a large quantity of data in building and characterizing test beds and performing tests. Although several data management systems were used to some extent, project-related data (e.g. scheduling, meeting notes, approvals and certifications) were handled on a commercial cloud system (Google Drive), while scientific data of interest to EGS and subsurface science was managed using the National Renewable Energy Laboratory's (NREL's) Data Foundry, which allows researchers to publish data to the Geothermal Data Repository and release it to the community. The Data Foundry had designated someone to be an active data manager who modified the system as needed to improve its performance and ease of use over time. This system was maintained as the backbone of project data management.

We live-streamed data during active experiments to enable our nation-wide team members to contribute to real-time decisions. Edge computing methods were adopted to quickly organize, annotate, and present many streams of data *as soon as possible* in a readily understood manner for making informed engineering decisions (*Weers and Huggins*, 2019). These data summaries are also useful in identifying interesting data for prospective data consumers. Making experimental data reachable and accessible to a broader community helped both expand the perspectives to scientific and engineering interpretations as well as make many important discoveries. Temporal and/or spatial synchronization of multi-faceted data sets was found to reveal processes that may be obscured in individual measurements, and/or corroborate other data streams allowing for more definitive conclusions. Accessible data must be well-described to be useful, thus care is taken in composing metadata enabling extensive future use of the data.

3.2 Processing seismic data

We deployed an intensive seismic monitoring system in Testbed 1 to image the fracturing in the experimental rock volume through detection and location of microseismic events. In addition, active seismic time-lapse imaging was acquired simultaneously. A large number of sensors and their 3D distribution around the stimulation zone via the 6 monitoring wells were used to determine rapid, high-quality hypocenters with spatial resolution at the sub-meter level. The high sensitivity of the accelerometer pods allowed for production of an extensive event catalog that was refined by machine learning algorithms. These algorithms helped separate microseismic signals from noise such as rail traffic or triggering of the electrical resistance tomography (ERT) system.

Making the latest version of the event catalog available to many researchers allowed many analyses, and precise identification of fracture planes, even those in close proximity to each other. In contrast to the diffuse "clouds" often seen, the clear microseismic maps recovered provide excellent spatial (and temporal) constraints on the seismically active fracture planes. The value of these data was increased by an edge processing framework (rapid limited on-site automatic processing of the data) developed within the Collab project to allow for near-real-time event detection and location, which provided *nearly immediate feedback* to field operations. Edge analysis was required to interpret the very large data stream generated by 100 kHz continuous recording and the inability to immediately transfer the data. Seismic data streams from the fiber optic sensing system (DAS) have required more intensive analysis and interpretation, resulting in significant delays in the utilization of these data. New approaches are under development to speed up the use of these data.

3.3 Connecting geophysics, fractures, and flow systems

Geophysical and hydraulic measurements supplemented direct observation of complete cores, interpretation of image logs, and fracture/shear zone mapping in the testbed vicinity. Tracer tests characterized natural and newly created hydraulic fractures and flows in the testbed and allowed inference of connectivity between fracture sets. As data were collected, they were integrated into a discrete fracture network (DFN) model, which served as a basis for conceptualizing fracture flow pathways. Seismic, electrical, temperature, and tracer data each highlighted some fractures or connections allowing continued building and improving the model. This DFN model was built by a team in open discussion to ensure proper accounting for all data sets (Schwering et al., 2020).

A multi-pronged approach was implemented to characterize and monitor reservoir evolution during Experiment 1. The MEQ monitoring system was the primary tool used for imaging the propagation and extent of hydraulic fractures. Additional measurements such as flowrate, pressure, electrical resistance tomography (ERT), distributed fiber optic sensing (temperature - DTS, strain - DSS, and acoustic - DAS), downhole camera observations, and tracer testing were conducted during Experiment 1 as well. Tracer tests helped reveal the dynamic behavior of the test bed, where the proportions of flow through different fracture networks varied with time. This comprehensive monitoring system enabled comparison of detailed testbed behavior described by the entirety of the data to corresponding inferences derived from a single type of data. This comparison is useful for placing appropriate expectations, strengths, and caveats on inferences derived from a single data type. The comparison also describes the integrated, consistent, and dynamic behavior of the testbed as revealed by different monitoring and characterization data sets.

Despite characterization and monitoring major natural and created fractures at individual levels, there are challenges in disentangling the fracture system's thermal exchange/heat extraction in the testbed. Some individual fractures strongly dominated the system response, diverting injected water over time. Because of the scale of the Collab experiment and accessibility, we were able to understand such behavior that would be difficult to discern in standard geothermal or petroleum operations at this depth.

Reconstructing and orienting core provides critical information on the subsurface environment**.** If performed in a timely manner this furnishes ground-truth information. Immediate correlation to wireline measurements allows extension of the ground-truth information and more reliable interpretation of the wireline data.

Time-lapse measurements using multiple techniques, including simple hydrological to geophysical methods, improved the understanding of the initial system, *and* changes in the system. Joint interpretation of multiple data streams is key to providing additional understanding. Some Collab successes were related to our capacity to use many highly instrumented dedicated monitoring wells to fully surround the target zone with sensors, resulting in high accuracy hypocenter determination. This approach also enabled the deployment of relatively new techniques such as continuous active source seismic monitoring (CASSM) and dynamic electrical resistance tomography (ERT). While not all the techniques used in Collab are directly implementable in EGS because of the temperature and cost of application, their use at Collab provides a broader description of processes. The use of multiple modalities of fiber optic sensing (distributed temperature, acoustic, and seismic sensing

– DTS, DAS, DSS) has been extremely valuable at Collab, providing large volumes of high-quality data at relatively low cost.

3.4 Modeling fractured flow systems

A principal objective of the project is learning whether the capabilities of modern state-of-the-art simulators are sufficient to accurately predict stimulation, evolving fracture networks, and subsequently thermal energy recovery for the Collab experiments. Numerical simulations 1) supported or refined experimental designs, 2) estimated the magnitudes of the effects of the applied stimuli to obtain approvals to proceed, 3) forecasted outcomes of operational changes, and 4) provided an understanding of observed behaviors.

Confidence in numerical simulation was increased by including modelers beginning with a detailed understanding of the experiments including design, and the expert use of codes that incorporate known processes to the extent reasonable. Simulations were performed in near-real-time yielding reliable, high-quality solutions. The true value of numerical simulation comes from the understanding it provides regarding complex system behavior, allowing scientists and engineers to make informed choices about next steps and interpreting empirical observations.

We have completed numerous simulations and compared them to measurements and these comparisons provide levels of validation. It is evident here that the simulators, when used by experienced modelers seeking mechanistic explanations, can provide valuable information for planning, interpretation, process quantification, and system understanding. The ability to perform near-real time simulations to provide suggested explanations to observations attests to the confidence in the simulators, and the modeling and simulation *process*. Simulators were improved when differences between the simulations and measurements occurred, leading to an increase in confidence.

There are many remaining challenges in simulating fracture flow and heat extraction. Understanding the interplay between poroelastic, thermal, chemical, and biological processes is thought to be vital to interpreting injection-pressure data. The rates at which chemistry may impact flow can be surprisingly fast, complicating injectivity data interpretation. Even with the sophisticated measurement techniques available, it is not always possible to provide boundary condition measurements on the scale and at all locations that a mechanistic model may require.

Another challenge is modeling a dynamic system. In Experiment 1, the flow rates at locations where water was collected changed over time. It is unclear what processes are responsible for those changes and whether these processes are already included in the simulators or whether they need to be added. Without additional observations and data, one can only speculate on the causes. However, the models can be used to offer insights into processes and process magnitudes and provide a guide to the next measurements needed.

4.0 Concluding Remarks

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

Advances in data handling and availability have been key to making real-time decisions in the Collab tests. Edge computing was used along with machine learning algorithms to rapidly sort and locate MEQs. These provided indications of the growing fracture location, and real-time knowledge of fracture location allowed for experiment control. We have had the ability to tie disparate geophysical data streams together, allowing for an excellent description of processes that occurred including monitoring fracturing and observing flow. The many modeling tasks have aided significantly in experiment design and interpretation of results. Often, models were run in near-real time enabling rapid response to observed conditions. Well-described data are available, and are in use by the community.

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