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An Overview of the EGS Collab Project: Field Validation of Coupled Process Modeling of Fracturing and Fluid Flow at the Sanford Underground Research Facility, Lead, SD

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ABSTRACT

Enhanced Geothermal Systems (EGS) development will require an ability to accurately predict the flow rates and temperatures of the production wells over time. While simple in concept, complex heterogeneous fracture pathways can lead to channeling, short-circuiting, and premature thermal breakthrough complicating EGS. The EGS Collab project will establish a suite of intermediate-scale (~10-20 m) 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. These experiments will provide a means of testing tools, codes, and concepts that could later be employed under geothermal reservoir conditions at the Frontier Observatory for Research in Geothermal Energy (FORGE) and in EGS. We will perform well-controlled, in situ experiments focused on rock fracture behavior and permeability enhancement. Pre- and post-test modeling of each test will allow for model prediction and validation. Comprehensive instrumentation will be used to collect high-quality, high-resolution geophysical and fracture characterization and fluid flow data. These data will be analyzed and compared with models and field observations to further elucidate the basic relationships between stress, induced seismicity, and permeability enhancement. To the maximum extent achievable, we will observe and quantify other key governing parameters that impact permeability, and 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. The Sanford Underground Research Facility (SURF) in South Dakota was selected as the EGS Collab project experimental site based on the evaluation of information from several sites. Our team has designed and constructed the first field experiment planned for this project, which is supported by the US Department of Energy's Geothermal Technologies Office.

1. 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 total more than 500 GWe, much larger than the resource base hosted by conventional hydrothermal systems (Williams et al., 2008). Augustine (2016) provides an EGS resource estimate that is ten times larger that the USGS evaluation when considering the entire country and utilizing higher resource recovery factors. While these resource estimates indicate that EGS has a vast resource base and large potential to contribute to the nation's clean energy future, there are technological challenges associated with extracting and utilizing this resource. These challenges include the (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 large-scale commercial deployment of EGS resources for power generation will require addressing these technical barriers.

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Based on a thorough analysis of these challenges, the U.S. Department of Energy's (DOE) Geothermal Technologies Office (GTO) developed a technology roadmap for advancing the deployment of EGS resources (Ziagos et al., 2013). This roadmap has led to the development of a robust R&D program directed at EGS that includes several EGS field demonstration projects at systems such as The Geysers, Desert Peak, Raft River, and Newberry Caldera (e.g., Garcia et al., 2016; Bonato et al., 2016; Bradford et al., 2016; Cladouhos et al., 2016), as well as the Frontier Observatory for Research in Geothermal Energy (FORGE), the DOE's flagship EGS research effort. FORGE, which is currently in the Phase II site-selection process (e.g., Blankenship et al., 2017; Allis et al., 2016), will create a full-scale field laboratory focused on developing, testing, and validating technologies to improve EGS reservoir characterization, access, creation, and sustainability. While FORGE will develop the most heavily instrumented full-scale EGS research site to-date, the target EGS field laboratory will be deep (> 1.5 km depth) and hot (T=175-225°C), and thus the associated cost of borehole access will necessarily limit process observations.

To facilitate the success of FORGE, the DOE GTO has initiated a new research effort, the EGS Collab project, which will utilize readily accessible underground facilities that can refine our understanding of rock mass response to stimulation and provide a test bed at 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. The EGS Collab 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. This project is a multi-lab and university collaborative research endeavor that brings together a team of skilled and experienced scientists 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.

Three experiments, each consisting of multiple tests, are planned to increase understanding of hydraulic fracturing, shear stimulation, and other stimulation methods. Each test will be modeled to aid in experiment design, and modeled following the test to examine the effectiveness of and improve the modeling tools. The suite of experiments will include multiple phases beginning with induced hydraulic fractures and proceed to shear stimulation of natural fractures and fracture networks with increasing complexity. The EGS Collab project will test a suite of methods that may be used to characterize and simulate an EGS system under the deep, hot conditions of FORGE as well as other methods available to improve understanding. The planned experiments will use 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). The planned suite of experiments furthermore can 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. EGS Collab Project Objectives and Organization

2.1 Project objectives

The stimulation and fluid flow experiments proposed for EGS Collab will provide the THMC modeling community with rich data sets that can in turn 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 which 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. Modelers assist in the design of 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 permeability of the fracture. The modeling work will build upon the advances achieved by the DOE GTO Code Comparison study (e.g., White et al., 2017a), which has helped to elucidate the challenges and complexities associated with modeling the stimulation of fractured rock masses. Although the development of new modeling tools is not a primary goal of the project, this 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 (Frash et al., 2018).

Data on fracture permeability enhancement mechanisms (e.g., slip on existing fractures, new fracture generation, and mixed-mode fracturing) will be gathered through carefully designed fracturing and fluid-flow experiments. Variability in fracture characteristics and related micro-seismicity as a function of in situ stress and stimulation processes will be monitored using multiple approaches in the high-density borehole arrays.

We propose three major experiments extending over the three-year project duration. Each experiment is composed of a number of stimulation and interwell flow tests. Each test requires:

- Pre−test modeling and site characterization to design the test and monitoring system
- Test execution with comprehensive monitoring including post- test characterization, and
- Thorough post- test modeling and validation.

In EGS Collab Experiments 1 and 2, we will create testbeds where we will perform and characterize a number of intensely monitored stimulations. Detailed measurements including stimulation behavior, permeability enhancement, and characteristics of the stimulated rock will provide insights into the nature of stimulation (e.g., hydraulic fracturing, hydroshearing, mixed-mode fracturing, thermal fracturing) in crystalline rock under reservoir-like stress conditions. The tests will also generate high-quality, high-resolution, diverse data sets for model validation. In addition, these tests will facilitate evaluation of monitoring techniques under controlled conditions to allow selection of technologies appropriate for deeper full-scale EGS sites. EGS Collab Experiments 1 and 2 will be performed under different stress/fracture conditions, and will evaluate different stimulation processes: Experiment 1 will focus on hydrofracturing, while Experiment 2 will concentrate on hydroshearing of an existing fracture. Conducting multiple tests under different conditions is important because it provides appropriate data for model comparison and leads to a better understanding of different stimulation mechanisms and their efficacy in creating reservoir permeability.

For EGS Collab Experiments 1 and 2, the experiment progression consists of:

- Testbed selection and preparation, including pre-stimulation modeling, monitoring design, borehole drilling, logging, core analysis, and stress measurement for site characterization,
- Stimulation test design refinement based on full site characterization,
- First stimulation with comprehensive geophysical, hydrological, and geomechanical monitoring,
- Interwell flow tests with tracers for geophysical, hydrological, geomechanical, and thermal characterization of the first stimulated network with comprehensive modeling,
- Second stimulation to create multiple stimulated zones and monitoring in the same testbed,
- Interwell flow test with tracers for geophysical, hydrological, geomechanical, and thermal characterization of the second stimulated network,
- Coreback to verify fracture properties.

These testbeds are being designed to exploit zones with different natural fracture densities, orientations, and stress states to span a variety of conditions, which might yield tensile fracturing, hydroshearing, and mixed-mode fracture networks. Each testbed will be constructed with an injection borehole, a production borehole, and multiple monitoring boreholes to allow a range of investigations including different stimulation approaches, seismicity measurement and its relationship with permeability creation, geophysical monitoring techniques, flow geometries, and the efficacy of zonal isolation. The testbeds will be designed to allow a sequence of tests by way of multistage stimulations, providing a path for replication or varying stimulation conditions within a single testbed. This combination of repeat tests, multiple monitoring wells, and inexpensive multistage completions can only be accommodated at a deep mine site where low cost drilling provides access to reasonable in situ stress conditions.

EGS Collab Experiment 3 will begin in year 3 and will investigate alternate stimulation and operation methods to improve heat extraction in an EGS reservoir (Mattson et al., 2018). We envision this task as conducting new experiments in the testbeds prepared for EGS Collab Experiments 1 and 2, improving on stimulations previously performed, and performing new stimulations with alternate methods (different fluid properties, different pressure applications, use of proppants, or other high-risk high-reward methods that can be evaluated in a scaled environment).

2.2 Team organization

Our EGS Collab team consists of a collection of top scientists and engineers from institutions including Lawrence Berkeley National Laboratory (LBNL - the lead organization), Sandia National Laboratories (SNL), Lawrence Livermore National Laboratory (LLNL), Pacific Northwest National Laboratory (PNNL), Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Stanford University, the University of Wisconsin, South Dakota School of Mines & Technology, the University of Oklahoma, Penn State University, and the Colorado School of Mines. To carry out such a complex series of experiments with such a large team, we have developed a matrix structure to integrate and coordinate our activities. The matrix consists of a series of task groups, associated with each major project phase, and also a number of working groups, associated with different activities. There are a total of 14 task groups distributed over the 3 experiments and 8 working groups maintaining continuity. The project is overseen by an executive committee consisting of the project PI and co-I, the EGS Collab project manager, a representative from each of the participating national laboratories, a representative for the university participants, a representative from each of the two FORGE projects, and the DOE EGS program manager and several GTO team members.

The tasks include: 1) Project Management; 2) Site Selection, Preparation, Drilling and Coring, Characterization (Experiment 1); 3) Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (Experiment 1); 4) Stimulation Test – Permeability Enhancement Execution and Characterization (Experiment 1); 5) Interwell Flow Test – Geophysical and Hydrological Characterization and Drillback (Experiment 1); 6) Feasibility Evaluation of Potential Stimulation Methods. (Experiment 3); 7) Site Selection, Preparation, Drilling and Coring, Characterization (Experiment 2); 8) Integration, Lessons Learned and Application to FORGE (Experiment 1); 9) Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (Experiment 2); 10) Stimulation Test (Experiment 2); 11) Interwell Flow Test – Geophysical and Hydrological Characterization (Experiment 2); 12) High Temperature Laboratory Experimentation to Support EGS Stimulations; 13) Alternative and Improved Stimulation Demonstration (Experiment 3); 14) Project Integration, Lessons Learned and Application to FORGE (Experiments 1, 2, 3). The eight working groups complement the task activities. These are: 1) Site Operations; 2) Geologic, Geomechanical, and Hydrologic Characterization; 3) Experiment Design; 4) Field Testing and Stimulation; 5) Monitoring; 6) Laboratory Experiments and Measurements; 7) Modeling and Simulation; 8) Integration, Upscaling, Application to FORGE.

The experiments will take place over a three-year period. The team envisions siting, designing, and initiating Experiment 1 during the first year. All data generated by the project will be managed using a data system developed for the Collab project (Weers and Huggins, 2018) and uploaded to the Geothermal Data Repository. Our project team envisions generating numerous publications and presentations from the planned activities, which will directly support the field investigations and associated modeling work planned for the next phase of FORGE.

3. EGS Collab Test Bed

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 (Fig. 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 world-class 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 minimal 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 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. Also, as a former working mine and current active site for physics research, 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.

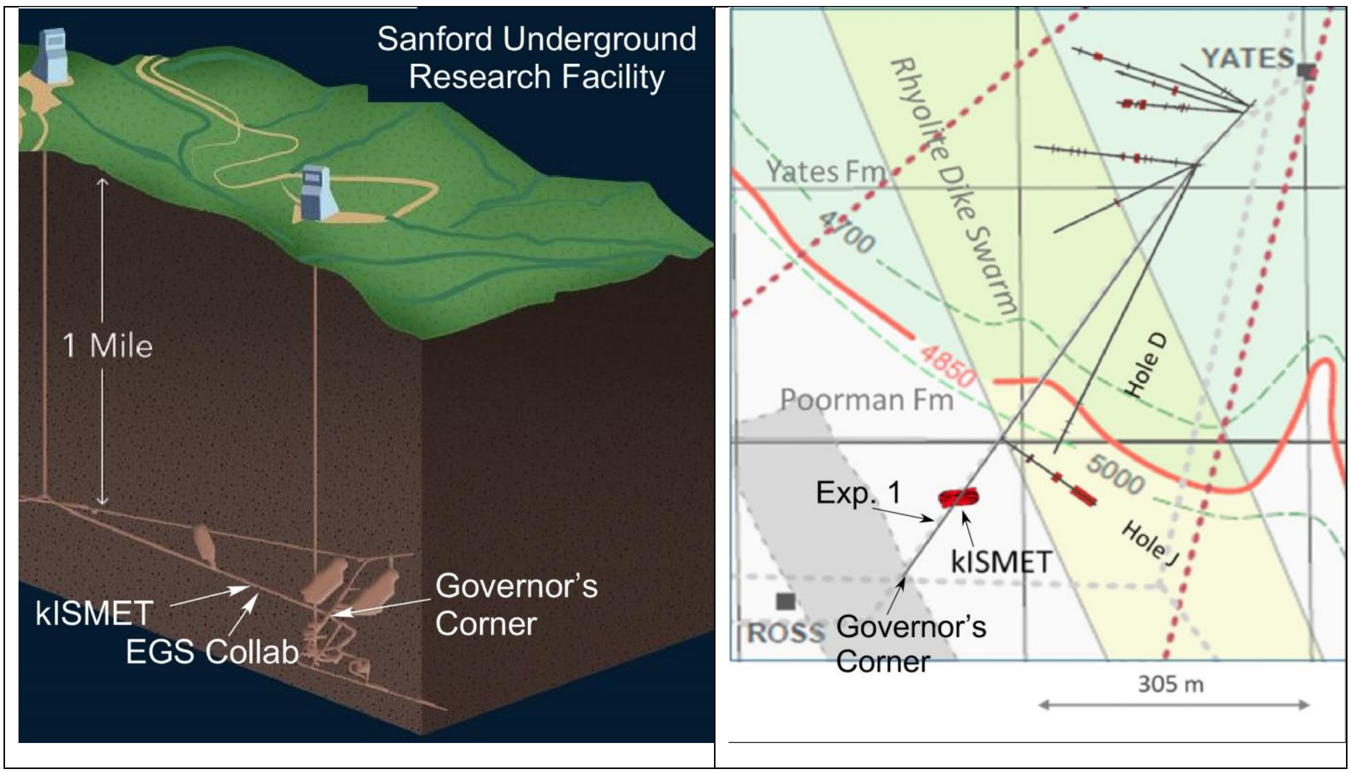

Figure 1: a) Schematic view of the Sanford Underground Research Facility (SURF), depicting a small fraction of the underground facilities including the Yates (left) and Ross (right) shafts, the 4850 level, and the locations of the kISMET experiment, and Experiment 1. b) Geologic map of the 4850 level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

3.2 Results of the kISMET project at SURF

A significant reason that the SURF was selected for the EGS Collab project is that this site was well characterized for this type of work during the kISMET project (Oldenburg et al., 2016). 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 hydrofracturing 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 hydrofracture experiments and the four surrounding 50 m deep HQ boreholes used for monitoring purposes. Pre-stimulation numerical modeling was used to estimate the breakdown pressure, propagation pressure, fracture geometry, and the magnitude of induced seismicity using a newly developed fully coupled three-dimensional (3D) network flow and quasi-static discrete element model (Zhou et al., 2017). 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. A series of stress measurements was conducted in the lower portion of the central borehole (see Figure 4), followed by a longer-term hydrofracture experiment at a depth of 40.23 m below the 4850 level drift invert. The shear fractures generated from these tests (Fig. 2) indicate that S_{hmin} is about 21.7 MPa (3146 psi) and is oriented N-S (356 degrees azimuth) with a plunge slightly NNW at 9° (Wang et al., 2017, Tom Doe, 2017, personal communication). The vertical and horizontal maximum stresses are similar in magnitude at ~42-44 MPa (6090-6380 psi) for the depths of testing (~1530 m). Monitoring techniques employed during the fracture experiments at kISMET included CASSM, ERT, micro-earthquake (MEQ) monitoring, and pressure and flow rate monitoring in the injection borehole. Review of previous borehole stress measurements and stress indicators in other boreholes on the 4850 level was also conducted.

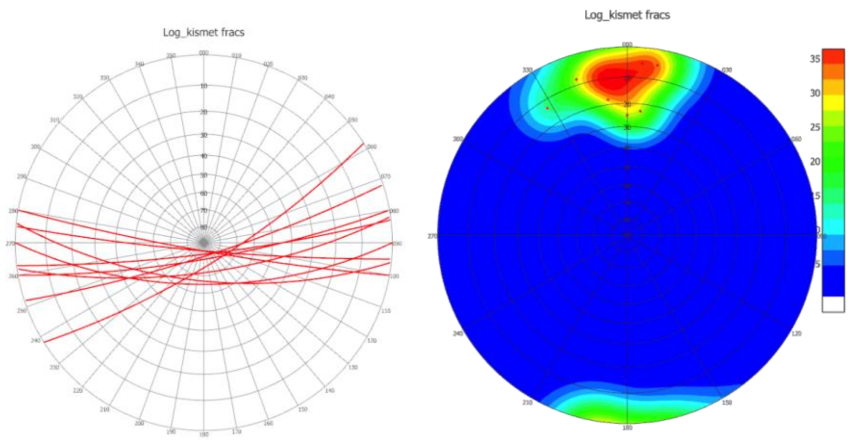

Figure 2: Orientation of fractures in kISMET 003 borehole. The stress orientations for the nearby Experiment 1 site are presumed to be similar to those obtained for the kISMET

4. Experiment 1 Description and Unexpected Conditions

4.1 EGS Collab Experiment 1

Based on the evaluation of available data and the results of an initial site visit by the EGS Collab team to SURF in April, 2017, the Experiment 1 site was chosen to be located in the vicinity of the kISMET site along the West Drift on the 4850 Level (Fig. 1). This area was selected 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 hydrofracture experiment
- Drift size and orientation conducive for drilling planned boreholes and carrying out subsequent experimental activities

Initial modeling work has been conducted to estimate the volume of fluid required to create a 20 m radius fracture (~110 L), and to estimate possible fracture apertures (~0.1 mm) (Fu et al., 2018). The initial modeling efforts (White et al., 2017b, White et al., 2018) have focused on addressing a number of initial questions to help guide experiment design including: 1) What is the preferred orientation for the stimulation borehole to meet the project objectives? 2) What anticipated number and magnitudes of seismic events during hydraulic stimulation? 3) What flow rates and pressures should be used for the circulation experiments to prevent fracture propagation?, 4) What circulation duration is required to achieve measureable temperature changes in the production borehole?, 5) Can the production well serve to prevent fracture propagation to the drift?, 6) Will a transverse hydraulic fracture form from the unaltered injection borehole drilled in the direction of σ_h, or is notching required?, 7) How does notch geometry impact stimulation pressure and near wellbore impedance? 8) What is the thermal profile around the drift? 9) How is the stress state altered in the experimental volume via mechanical and thermal alteration from the mine workings and drift cooling?, and 10) What is the anticipated shape and arrival time in terms of injected fluid volume of the hydraulically generated fracture under the mechanically and thermally altered stress state?

A borehole configuration for the first experiment was developed (Fig. 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 hydrofractures), 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.

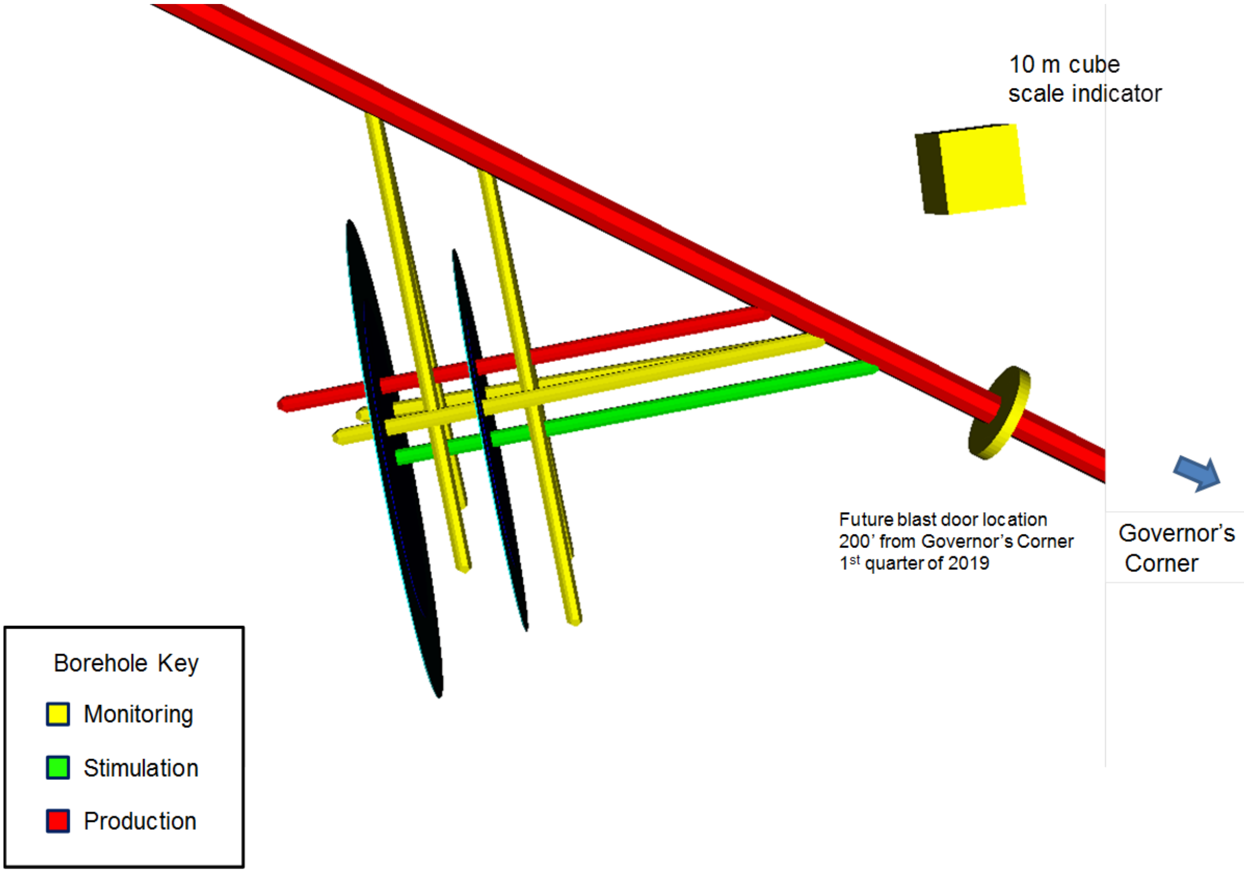

Figure 3: Plan view schematic layout of boreholes for Experiment 1 location along the West Drift on the 4850 level of SURF. Black disks represent potential radial fractures generated through hydrofracture experiments. The green borehole represents the stimulation well, the red borehole represents the production well for flow experiments, and yellow boreholes represent monitoring wells. Orientation of stimulation and monitoring boreholes is approximately parallel to S_{hmin}.

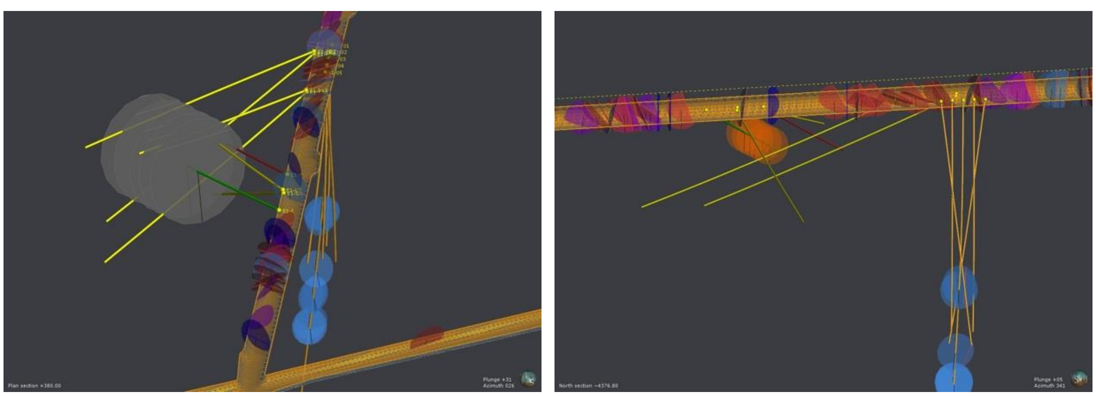

Figure 4: Oblique views of the as-built Experiment 1 test site. Drift (tunnel) floors are shown as the wide orange troughs. The subvertical kISMET wells are orange, and the stress measurement tests performed in k003 are shown as light blue circles. Various colored circles along the drift indicate observed 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 (left) and orange circles (right) indicate potential stimulated fractures from placed notches. Left: View from above right of Governor's Corner. Right: ~Horizontal view from beneath east side of drift.

We developed an initial geologic framework model in Leapfrog (Aranz Geo Limited). Initial geologic data contained in the Maptek Vulcan database for SURF (e.g., Hart et al., 2014), available geotechnical reports, and the kISMET study (Oldenburg et al., 2016) are used to create 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 on the 4850 level. As additional geologic information is obtained, these models are updated. Currently the geologic framework model incorporates as-built boreholes and mapped fractures (Fig. 4). The geologic framework model will be critical in constraining the grid block properties for the coupled process models simulating the EGS Collab experiments and provide a more uniform basis for model comparison.

Experiment 1 borehole drilling was completed in December 2017, and detailed characterization of the rock mass is underway. Borehole logging tools including resistivity, full-waveform sonic, temperature, conductivity, optical televiewer, and acoustic televiewer have been utilized and data are being analyzed. Over 400 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 will also be conducted prior to and after the hydrofracture experiments. The existing kISMET boreholes have been utilized to measure temperature gradients away from the drift walls. All of 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, Newman and Petrov, 2018, Huang et al., 2017); 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 et al., 2018); 4) Acoustic emissions (Zang et al., 2017); 5) Distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), and strain (DSS) changes (Daley et al., 2013); 6) Fracture aperture strain monitoring using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool (Guglielmi et al., 2013, Guglielmi et al., 2015); 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 (Knox et al., 2016, Huang et al., 2017, Newman and Petrov, 2018).

Two hydrofracture experiments will be conducted at the Experiment 1 site in the injection borehole using a pump-packer assembly housing the SIMFIP tool (Knox et al., 2017). To help initiate the fractures in the proper orientation, the boreholes were notched (White et al. 2018, Morris et al., 2018). After a through-going fracture is created between the injection and production well, a series of flow experiments using a suite of selected tracers and ambient and chilled fluids will be conducted to evaluate flow properties, permeability enhancement, and to constrain the coupled process (THCM) fracture stimulation and fluid flow models (Knox et al, 2017, Zhang et al., 2018). Image logging of the boreholes and a core hole drilled through the fracture network after the experiments will provide additional details on the nature of the fractures that were created. 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).

The results of the first experiment will be used to help design Experiments 2 and 3. Careful integration between the characterization, field experiment design, field operations, modeling, laboratory measurement, and monitoring teams is necessary for this project to be successful. Our initial activities have helped build a dynamic team spirit that cuts across institutional and disciplinary boundaries, which bodes well for the outcome of this project.

4.2 Unexpected Conditions

The Experiment 1 site is located tens of meters from the kISMET boreholes. Observations from these kISMET subvertical boreholes including extracted core led us to think the rock could generally be described as 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 have identified a number of features. Although the Experiment 1 site characterization is currently ongoing, the subhorizontal boreholes have intersected a number of fractures. Two boreholes intersect a relatively open fracture, as water flows between these holes. Another borehole intersects a water-filled or flowing fracture network, and continues to produce water at a low rate six weeks after drilling has been completed. The decline in flowrate, and subsequent increase following logging, in combination with observations of rusty-looking slime on the drift wall where the water drains, leads to the question of the presence of biota (Osburn et al., 2014). 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.

5. Anticipated Results of the EGS Collab Project

At the conclusion of the three-year EGS Collab project, we anticipate achieving the following results:

- Completion of a series of well-constrained and highly monitored field fracture stimulation and fluid flow experiments under a variety of regional stress, fracture stimulation, and cross-well flow conditions.

- A suite of comprehensively tested and validated THMC simulators capable of modeling fracture generation and propagation under a variety of stress, pressure and temperature regimes in crystalline rock, either initially unfractured or with pre-existing fractures.

- A suite of flow simulators that accommodate a variety of complex fracture geometries and multiple injector/producer well geometries that match both physical and chemical system evolution.

- Advancement of geophysical and other monitoring capabilities towards the goal of imaging fluid pressure and fracture permeability that can be adapted to the FORGE testbed.
- Full integration of predictive and inverse modeling, experimentation, prior and posterior imaging that will translate seamlessly to the FORGE testbed.
- Improved process knowledge to enhance design of effective stimulation in EGS.
- A number of testbeds with different stress/fracture conditions that could be used to perform follow-on experiments, including but not limited to inexpensive tool and method checks related to FORGE.

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