An Introduction to the EGS Collab Project

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ABSTRACT

The development of Enhanced Geothermal Systems (EGS) requires an ability to accurately predict the flow rates and temperatures of the production wells. While simple in concept, EGS is complicated by the heterogeneity and complexity of fracture pathways that can lead to channeling, short-circuiting, and premature thermal breakthrough. The EGS Collab project will

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establish a suite of intermediate-scale (~10-20 m) field test beds coupled with stimulation and interwell flow tests that will provide a basis to better understand the fracture geometries and processes that control heat transfer between rock and stimulated fractures. As such, the EGS Collab experiments will provide a relatively inexpensive means of testing tools and concepts that could later be employed under geothermal reservoir conditions at FORGE. Our tests will be 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 and high-resolution geophysical and other fracture characterization and fluid flow data, and 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. Evaluation of site criteria led the team to choose the Sanford Underground Research Facility (SURF) in South Dakota as the EGS Collab project experimental site. Our team is well underway with designing 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, the technological challenges associated with extracting and utilizing this resource make it uneconomic under current market conditions. Examining historical and active EGS projects has led to identification of a number of technical barriers that have limited the progress of EGS, such as (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 reservoir sustainability and management techniques. The development of EGS will require addressing these technical barriers.

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 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 (on the order of 10 m) scales for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches as well as novel monitoring tools.

EGS Collab tests the hypothesis that there is a set of characterization and numerical simulations tools that can predict the thermal performance of an EGS system. 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). A key to the project is a thermal circulation experiment that will validate predictions based on field data and stimulations. 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. The planned suite of experiments furthermore can develop new monitoring methods that are currently unable to work under geothermal reservoir conditions.

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. 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.

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 a rich data set that can in turn be used to validate the capabilities of predictive models that will be employed to support FORGE. The smaller scale nature of these experiments will allow for proximal monitoring through multiple boreholes leading to high-resolution geological and geophysical characterization of the rock mass before, during, and after stimulation. Modelers will 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.

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 smaller experiments or tests of stimulation and interwell flow; each of which require:

- 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 Experiments 1 and 2, we will create testbeds where we will perform and characterize a number of intensely monitored stimulations. Detailed measurements of 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 and 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 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. Having multiple tests conducted 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 Experiments 1 and 2, the experiment progression consists of:

- Testbed selection and preparation, including pre-stimulation modeling, monitoring design, borehole drilling, 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 will be designed to exploit zones with different natural fracture densities 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 also be designed to allow a sequence of tests by way of multistage stimulation, 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 Experiment 3 will begin in year 3 and will investigate alternate stimulation and operation methods to improve heat extraction in an EGS reservoir. We envision this task as conducting new experiments in the testbeds prepared for EGS 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 LBNL (the lead organization), SNL, LLNL, PNNL, INL, LANL, NREL, 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 and 8 working groups. 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.

The task groups are as follows: 1) Project Management; 2) Site Selection, Preparation, Drilling and Coring, Characterization (EGS Experiment 1); 3) Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring Design and Installation (EGS Experiment 1); 4) Stimulation Test – Permeability Enhancement Execution and Characterization (EGS Experiment 1); 5) Interwell Flow Test – Geophysical and Hydrological Characterization and Drillback (EGS Experiment 1); 6) Feasibility Evaluation of Potential Stimulation Methods. (EGS Experiment 3); 7) Site Selection, Preparation, Drilling and Coring, Characterization (EGS Experiment 2); 8) Integration, Lessons Learned and Application to FORGE (EGS Experiment 1); 9) Refine Stimulation Test Design, Preliminary THMC Test Design Modeling, and Monitoring

Design and Installation (EGS Experiment 2); 10) Stimulation Test (EGS Experiment 2); 11) Interwell Flow Test – Geophysical and Hydrological Characterization (EGS Experiment 2); 12) High Temperature Laboratory Experimentation to Support EGS Stimulations; 13) Alternative and Improved Stimulation Demonstration (EGS Experiment 3); 14) Project Integration, Lessons Learned and Application to FORGE (EGS Experiments 1, 2, 3).

The project also has eight different working groups that 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 different phases of the project (represented by the tasks) 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 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 site criteria led the team to choose the Sanford Underground Research Facility (SURF) in South Dakota as the EGS Collab project experimental site (Fig. 1). SURF is located in the former Homestake gold mine in Lead, SD, 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 replicate temperature-induced effects in the field (e.g., using chilled or heated brines to induce a differential temperature) or via complementary laboratory experiments involving high-temperature measurements; similar options do not exist to replicate stress. At depths of approximately 1500 m, 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.

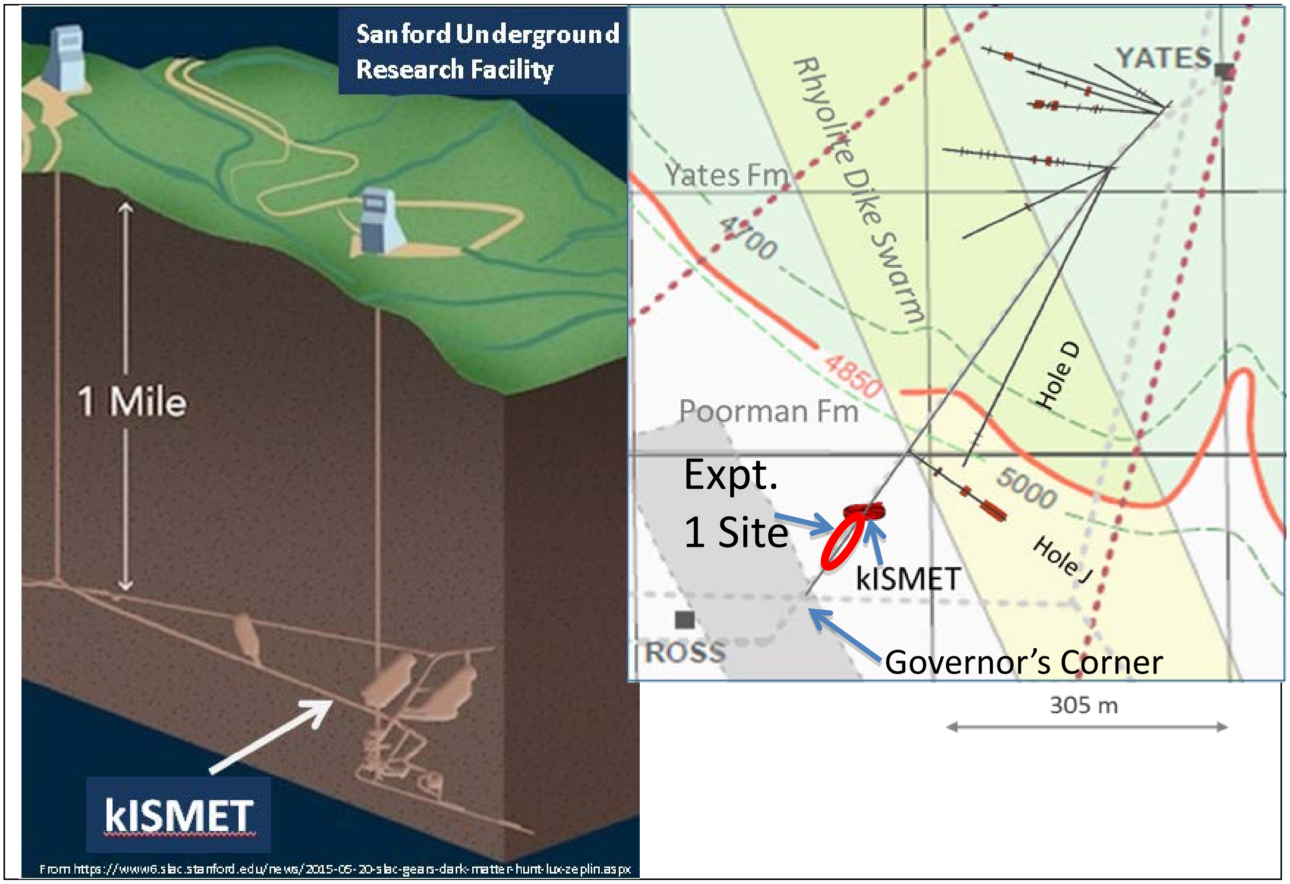

Figure 1: a) Schematic view of the Sanford Underground Research Facility (SURF), depicting the Yates (left) and Ross (right) shafts, the 4850 level, and the location of the kISMET experiment. b) Geologic map of the 4850 level of SURF in the vicinity of the proposed experiment site for Experiment 1 of SIGMA-V. Both of these areas are located along the West Drift between the rhyolite dikes and Governor's Corner (the bottom left corner of the main triangle of drifts). The proposed location for Experiment 1 is located between the kISMET site and Governor's Corner.

3.2 Results of the kISMET project at SURF

One of the reasons why the SURF site 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 boreholes on the 4850 level of SURF in a five-spot configuration, 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 of 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, 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 12° (Wang et al., 2017). 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 that were 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.

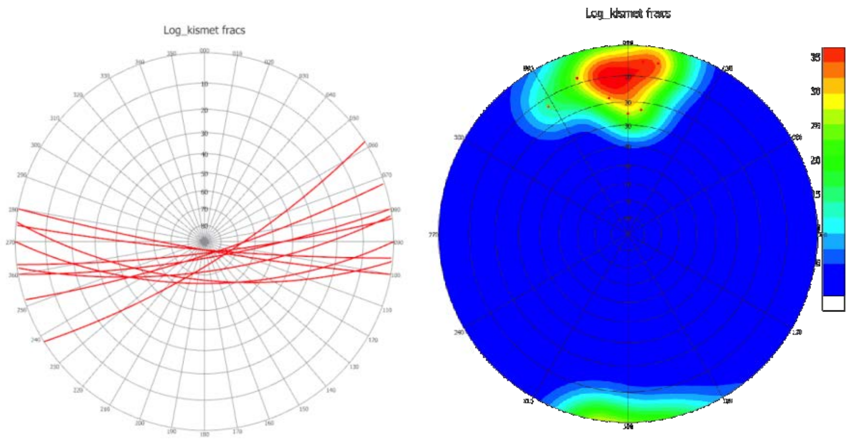

Figure 2: Orientation of fractures in kISMET 003 borehole. The stress orientations for the EGS Collab Experiment 1 site are presumed to be similar to those obtained for the adjacent kISMET site.

4. Next Steps for EGS Collab: Experiment 1

Based on 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 (unfractured) 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 already been conducted to evaluate the volume of fluid that would need to be injected to create a 20 m radius fracture (~110 L), and to estimate possible fracture apertures (~0.1 mm). The initial modeling effort (White et al., 2017b) has focused on addressing five initial questions to help guide experiment design: 1) What is the preferred borehole orientation? 2) Does the stimulation borehole need to be notched? 3) How would the notch geometry impact stimulation pressure and near-wellbore impedance? 4) What frequency and magnitude of microseismicity would be generated by the stimulation? 5) What should be the duration of the planned chilled water thermal test?

Based on coordination between the Experiment 1 characterization, design, stimulation, and flow test task groups and the characterization, modeling, experiment design, and monitoring working groups, a preliminary borehole configuration for the first experiment was developed (Fig. 3). This design is based on having near-horizontal stimulation and production boreholes with a slight down dip that are oriented perpendicular to the orientation of the expected hydrofractures, and that are spaced 10 meters apart. A suite of monitoring boreholes is planned to 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.

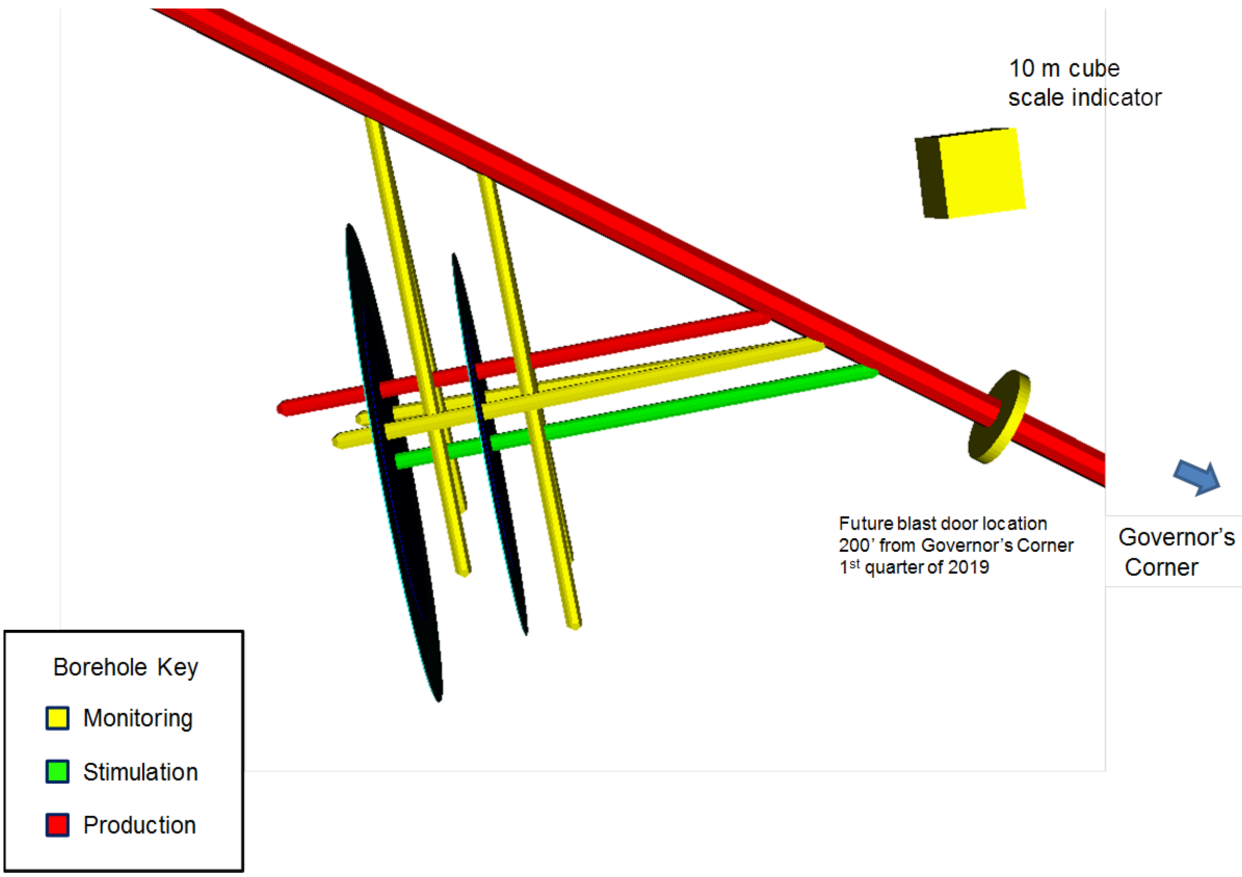

Figure 3: Plan view schematic layout of boreholes for Experiment 1 location along the West Drift on the 4850 level of SURF. Black disks represent potential radial fractures generated through hydrofracture experiments. Green borehole represents stimulation well, red borehole represents production well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

An initial geologic framework model is being developed using Rockworks 17 software (RockWare Inc., Golden, CO). 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 being 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 will be updated. The geologic framework model will be critical in constraining the grid block properties for the coupled process models simulating the EGS Collab experiments.

After drilling of the boreholes, detailed characterization of the rock mass will be conducted. Retrieved core will be logged to identify foliation, veining, bedding, fractures, and variations in mineralogy. All of the boreholes are expected to be 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 the hydrofracture experiments. The existing kISMET boreholes have been utilized to measure temperature gradients away from the drift walls. All of these data will be integrated into the geologic framework model of the Experiment 1 site.

The suite of monitoring methods will be expanded beyond what was used in the kISMET hydrofracture experiments to provide the necessary field data needed to constrain the coupled process models. These methods include: 1) Passive seismic monitoring; 2) CASSM; 3) ERT in conjunction with dynamic electrical imaging using high contrast fluids; 4) Acoustic emissions; 5) Distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), and strain (DSS) changes; 6) Fracture aperture strain monitoring using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool; 7) Continuous monitoring of pressure and flow conditions in the injection and production boreholes; 8) Tracer tests; 9) Borehole strain monitoring using tiltmeters; 10) Wavefield imaging and inversion.

Two hydrofracture experiments will be conducted at the Experiment 1 site in the injection borehole using a pump-packer assembly similar to what was utilized in the kISMET experiment. After a through-going fracture has been 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. 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.

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.

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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REFERENCES

Allis, R., Moore, J., Davatzes, N., Gwynn, M., Hardwick, C., Kirby, S., McLennan, J., Pankow, K., Potter, S., and Simmons, S. "EGS concept testing and development at the Milford, Utah FORGE site." *Proceedings, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-209, (2016), 13 p.

Augustine, C. "Update to Enhanced Geothermal System Resource Potential Estimate." *Geothermal Resources Council Transactions*, 40, (2016), 673-677.

Blankenship, D., Kennedy, M., Majer, E.L., Hinz, N., Faulds, J., Ayling, B., Blake, K., Tiedeman, A., Sabin, A., Lazaro, M., Akerley, J., Siler, D., Kaven, J.O, Phelps, G., Hickman, S., Glen, J., Williams, C., Robertson-Tait, A., Hackett, L., Pettitt, W. "Proposed Fallon FORGE site: Phase 2 update." *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-212, (2017), 7 p.

Bonato, S., Hickman, S., Davatzes, N.C., Taron, J., Spielman, P., Elsworth, D., Majer, E.L., and Boyle, K. "Conceptual model and numerical analysis of the Desert Peak EGS project: Reservoir response to the shallow medium flow-rate hydraulic stimulation phase." *Geothermics*, 63, (2016), 139-156.

Bradford, J., McLennan, J., Tiwari, S., Moore, J., Podgorney, R., Plummer, M., and Majer, E. "Application of hydraulic and thermal stimulation techniques at Raft River, Idaho: A DOE Enhanced Geothermal System Demonstration Project. *50th US Rock Mechanics / Geomechanics Symposium*, ARMA 16-858, (2016), 5 p.

Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., and Otto, R.P. "The Homestake gold mine, an early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota." *USGS Bulletin* 1857, Chapter J, (1991), 67 p.

Cladouhos, T.T., Petty, S., Swyer, M.W., Uddenberg, M.E., Grasso, K., and Nordin, Y. "Results from Newberry Volcano EGS Demonstration, 2010-2014." *Geothermics*, 63, 44-61.

Doe, T.W., McLaren, R., and Dershowitz, W. "Discrete Fracture Network Simulations of Enhanced Geothermal Systems." *Proceedings, 39th Workshop on Geothermal Reservoir Engineering*, Stanford University (2014), SGP-TR-202, 11 p.

Garcia, J., Hartline, C., Walters, M., Wright, M., Rutqvist, J., Dobson, P.F., Jeanne, P. "The Northwest Geysers EGS Demonstration Project, California Part 1: Characterization and reservoir response to injection." *Geothermics*, 63, (2016), 97-119.

Hart, K., Trancynger, T.C., Roggenthen, W., and Heise, J. "Topographic, geologic, and density distribution modeling in support of physics experiments at the Sanford Underground Research Facility (SURF)." *Proceedings of the South Dakota Academy of Science*, 93, (2014), 33-41.

Heise, J. "The Sanford Underground Research Facility at Homestake." *Journal of Physics: Conference Series*, v. 606 (1), IOP Publishing, (2015).

Oldenburg, C.M., Dobson, P.F., Wu, Y., Cook, P.J., Kneafsey, T.J., Nakagawa, S., Ulrich, C., Siler, D.L., Guglielmi, Y., Ajo-Franklin, J., Rutqvist, J., Daley, T.M., Birkholzer, J.T., Wang, H.F., Lord, N.E., Haimson, B.C., Sone, H., Vigilante, P., Roggenthen, W.M., Doe, T.W., Lee, M.Y., Ingraham, M., Huang, H., Mattson, E.D., Zhou, J., Johnson, T.J., Zoback, M.D., Morris, J.P., White, J.A., Johnson, P.A., Coblentz, D.D., and Heise, J. "Hydraulic fracturing experiments at 1500 m depth in a deep mine: Highlights from the kISMET project." *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, (2017), 9 p.

Wang, H.F., Lee, M.Y., Doe, T.W., Haimson, B.C., Oldenburg, C.M., and Dobson, P.F. "In-situ stress measurement at 1550-meters depth at the kISMET test site in Lead, S.D." *51st US Rock Mechanics / Geomechanics Symposium*, ARMA 17-651, (2017), 7 p.

White, M.D., Fu, P., Huang, H., Ghassemi, A., and EGS Collab Team “The role of numerical simulation in the design of stimulation and circulation experiments for the EGS Collab project. *Geothermal Resources Council Transactions*, v. 41, (2017b).

White, M.D., Fu, P., and McClure, M.W. "Outcomes from a collaborative approach to a code comparison study for Enhanced Geothermal Systems." *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-212, (2017a), 12 p.

Williams, C.F., Reed, M.J., Mariner, R.H., DeAngelo, J., and Galanis Jr., S.P. "Assessment of moderate- and high-temperature geothermal resources of the United States." *USGS Fact Sheet* 2008–3082, (2008), 4 p., http://pubs.usgs.gov/fs/2008/3082/

Zhou, J., Huang, H., Mattson, E., Wang, H.F., Haimson, B.C., Doe, T.W., Oldenburg, C.M., and Dobson, P.F. "Modeling of hydraulic fracture propagation at the kISMET site using a fully coupled 3D network-flow and quasi-static discrete element model." *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-212, (2017), 11 p.

Ziagos, J., Phillips, B.R., Boyd, L., Jelacic, A., Stillman, G., and Hass, E. "A technology roadmap for strategic development of Enhanced Geothermal Systems." *Proceedings, 38th Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-198, (2013), 24 p.