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The EGS Collab Hydroshear Experiment at the Sanford Underground Research Facility – Siting Criteria and Evaluation of Candidate Sites

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Keywords

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ABSTRACT

The objective of the EGS Collab project is to 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. Experiment 1 of the project is being conducted at a depth of ~1.5 km in the Sanford Underground Research Facility (SURF) on the 4850 Level (ft. below the ground surface). The stimulation method planned for Experiment 2 of this project is hydroshearing of an existing natural fracture. In siting this experiment, there are several key geologic criteria that need to be met. These include: 1) the fracture should be least 10 m in length so that it could be intersected by two boreholes that are spaced that far apart; 2) it should be optimally oriented relevant to the stress field so that it is critically stressed; 3) the site should have appropriate stress conditions (not too shallow a depth); 4) the fracture should have sufficient permeability to allow for prestimulation flow testing, but not too high a permeability that would preclude permeability enhancement via shear stimulation; 5) the fracture should not intersect other features (permeable fractures, boreholes, adjacent drifts) that could serve as major leak-off zones; 6) the site should not be complicated by geology (a single lithology would be preferred). In addition, there are logistical criteria that will also influence site selection, including: 1) site availability/access, 2) logistical support, e.g., power, internet, water, operating rail system; 3) drift size and orientation compatible with drilling and site operations; 4) appropriate ground support. There are only two deep levels at SURF that can be accessed by the Yates Shaft: the 4100 and the 4850, so we limited our search to these two levels. Currently, three candidate sites are being evaluated: the existing Experiment 1 site and its surroundings on the West Drift on the 4850 level, and two locations on the 4100 level. This paper will evaluate advantages, disadvantages, and risks associated with these three options at SURF.

1. Introduction

The development of Enhanced Geothermal Systems (EGS) as sustainable and commercially viable resources will require an ability to accurately predict the flow rates and changes in temperature of fluids produced from production wells over time. Complex, heterogeneous fracture pathways can lead to channeling, short-circuiting, and premature thermal breakthrough, thus complicating EGS. To address these challenges, the EGS Collab project is developing a suite of intermediate-scale (~10-20 m) field test beds to conduct stimulation and interwell flow tests at the Sanford Underground Research Facility (SURF), located in Lead, SD. We have successfully created our first experimental test bed for EGS Collab Experiment 1 for conducting a series of hydrofracture stimulation and flow experiments on the 4850 level (1478 m below the surface) of SURF, a former gold mine, in the Precambrian Poorman Formation phyllite (Kneafsey et al., 2018; Morris et al., 2018). This test bed consists of a stimulation/injection borehole, a production borehole, and six monitoring boreholes (Fig. 1). The borehole layout was designed so that the axes of the injection and production boreholes are parallel to S_{hmin}, which will cause hydraulic fractures to be generated perpendicular to the boreholes. The locations for the hydrofractures were selected to minimize interaction with natural fractures.

A second set of experiments is planned for testing hydroshearing of natural fractures as a means of reservoir stimulation. This will require identification of a test bed that has natural fractures of the appropriate length and orientation relative to the local stress field that would enable them to be stimulated and provide a similar pathway between injection and production boreholes for subsequent flow tests. Logistical and economic constraints also will impact site selection at SURF. These factors are discussed in the following sections.

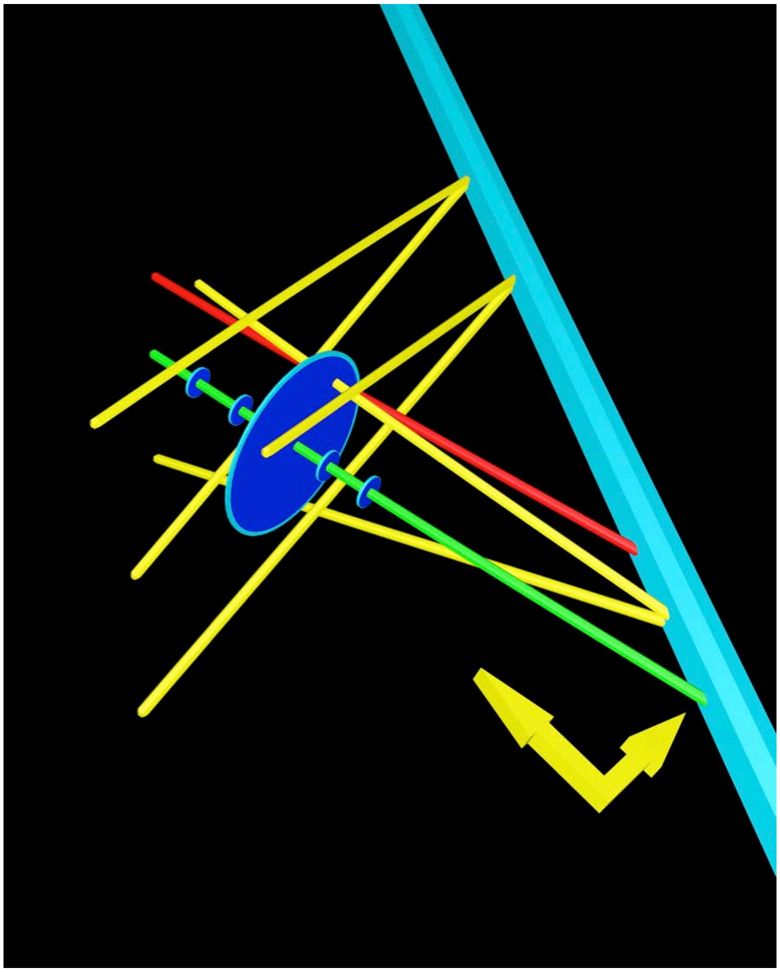

Figure 1: Layout of the EGS Collab borehole test bed developed on the 4850 Level (1478 m below ground surface) for fracture stimulation and flow experiments of Experiment 1 (Morris et al., 2018). Boreholes are ~60 m in length. The green borehole is the stimulation/injection borehole, the red borehole is the production borehole, and the yellow boreholes contain an array of sensors to monitor the experiments. The larger yellow arrow indicates north, the other points to the east. The blue discs represent zones in the stimulation well that were notched to facilitate hydrofracturing in the design direction, which is perpendicular to S_{hmin}; the larger blue disc is a conceptual fracture trajectory from a notched section of the borehole.

2. Criteria for Site Selection for Experiment 2

A number of geologic and logistical criteria need to be met in the selection of an appropriate site for Experiment 2 at the SURF site. The primary requirement for site selection is that the selected location has the appropriate fracture characteristics needed for conducting the hydrofracture experiment. In addition, there are a number of practical constraints regarding site features such as drift condition and width, availability of needed logistical support, and site availability at SURF that impact the project schedule and cost. Balancing the risks associated with each criterion will be required in making the final site selection. These factors are outlined in the section below.

2.1 Desired fracture characteristics

The primary objective of Experiment 2 for the EGS Collab project is to evaluate stimulation of natural fractures to enhance permeability through hydroshearing. Similar to Experiment 1, the tentative plan is to have the stimulation and production boreholes located 10 meters apart – thus the fractures that will be stimulated need to be at least that long and intersect both boreholes. If the fractures have some inherent transmissivity, this would be a plus, as it would enable conducting flow through experiments before and after shear stimulation to evaluate the effects of stimulation. Such features are evidenced by active weep zones observed within the drift (e.g. Roggenthen et al., 2018); the weep features are typically hosted by a fracture zone rather than a single fracture. Another requirement that needs to be met for hydroshearing to be successful is that the fractures should not intersect other highly permeable features that would serve as major leak-off zones during the stimulation. Finally, the fractures should be oriented relative to the local stress field such that they exhibit a high slip tendency, making them good candidates for hydroshearing (Morris et al., 1996; Ferrill et al., 1999; Walsh and Zoback, 2016). Stress measurements conducted at the kISMET site provide important constraints regarding the stress orientations and their magnitudes (Wang et al., 2017). The fracture stimulation experiments and the associated flow tests through the fracture network will be designed and simulated using coupled process models (e.g., White et al., 2018); thus having a site with simpler geologic conditions, such as having a single lithology, would make this process more straightforward.

2.2 Logistical concerns for site selection

A number of non-geologic aspects related to siting are also important considerations. First, the area where Experiment 2 will be conducted needs to be accessible to the EGS Collab team over the duration of the planned activities. There are many different groups conducting experiments at SURF (e.g., Heise, 2015), and the upcoming development of the Long Baseline Neutrino Facility on the 4850 level in the vicinity of Governor's Corner is the most extensive. Major blasting and excavation activities are planned in 2020, which may preclude conducting field activities at the current Experiment 1 location once this work commences. Another constraint is the need for a site with sufficient space for conducting drilling of boreholes and assembling all of monitoring and fracture stimulation gear (Fig. 2). A wide drift (~4 m) with a double track is best suited for being able to convey materials and allow access past the experimental equipment. The orientation of the drift relative to the desired fractures may also affect the ability to develop an effective test bed.

Other important features to consider in site selection are the physical condition of the site and the availability of needed utilities. The drift where the work will be conducted needs to have good ground support (rock bolts and mesh), and the area also needs access to power (typically 110, 230, and 480 volt service) to run the drill rig and the monitoring, rock stimulation, and flow experiment equipment. The site also needs access to mine water and water disposal, lighting, and robust internet connectivity to conduct and monitor the experiments. Rail car service is needed to transport people, equipment and materials to the experiment site. Sites that do not have these features would require extensive modifications, thus requiring a prolonged schedule and increased site preparation costs to meet experiment requirements.

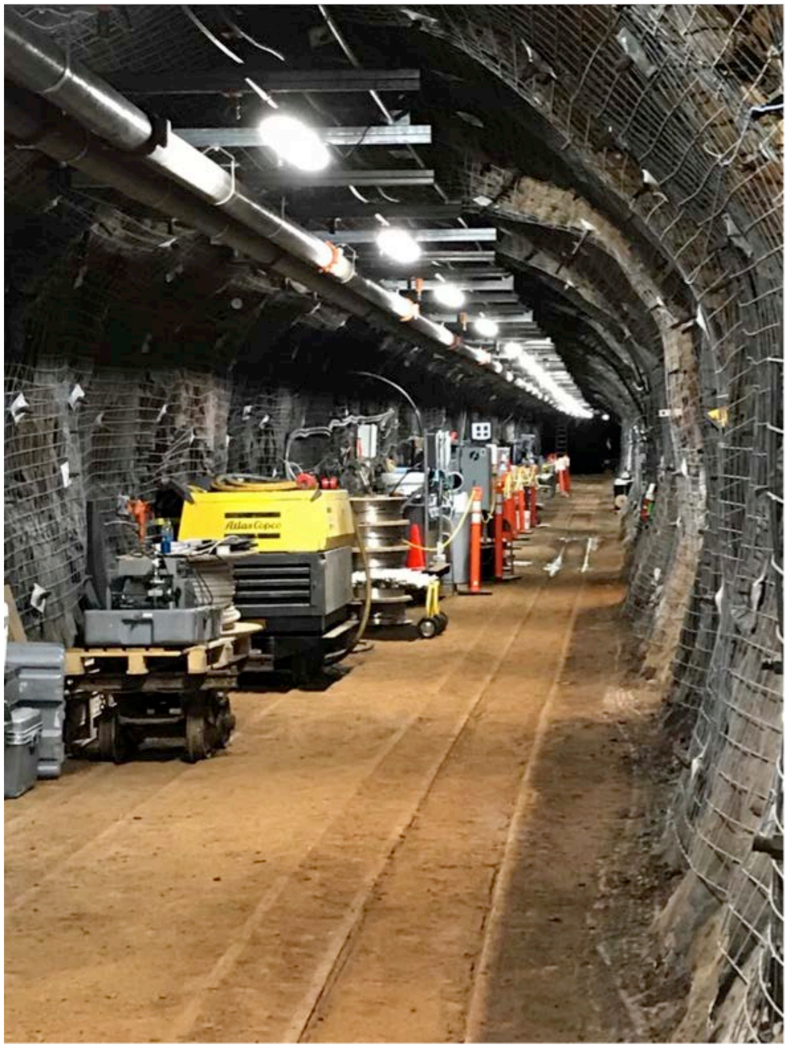

Figure 2: Deployment of monitoring and stimulation equipment in the West Drift on the 4850 level prior to conducting stimulation portion of Experiment 1. Note the extensive amount of gear (much mounted on rail cars) needed for the experiment. Having a wide drift with two rail lines provides access past the experiment.

3. Evaluation of West Drift area near Experiment 1 location on 4850 level

3.1 Advantages of the West Drift location on the 4850 level

There are a number of inherent advantages to siting Experiment 2 near or at the location of the Experiment 1 site. These are described below.

3.1.1 Prior site characterization

Detailed geologic studies of this area were conducted by the kISMET project (e.g., Oldenburg et al., 2017; Wang et al., 2017) and Experiment 1 of the EGS Collab project (e.g., Kneafsey et al., 2018; Roggenthen et al., 2018; Ulrich et al., 2018). The geology of this area is fairly straightforward, as only a single lithologic unit is present, 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). During drilling of the eight boreholes at the Experiment 1 site, small intervals of quartz-rich pods were encountered – this was the main geologic variant (and caused much slower drilling through these intervals). Continuous core samples from all of these boreholes were collected and described, and the boreholes were imaged using televiewer logs to characterize fractures, veins, and foliation (Kneafsey et al., 2018; Roggenthen et al., 2018; Ulrich et al., 2018). The geologic characterization work for kISMET and Experiment 1 of the EGS Collab project, along with prior geotechnical studies conducted for SURF, provide important constraints regarding the stress regime of this area as well as the orientation and distribution of natural fractures, as described in the following subsection.

3.1.2 Slip tendency of natural fractures

Mapping of natural fractures at the Experiment 1 site of the EGS Collab project was conducted by the study of core samples and acoustic televiewer logs from each of the eight boreholes depicted in Fig. 1. These fractures were incorporated into an earth model of the site using Leapfrog (Fig. 3). The software package "Fault Slip Potential", developed by the Stanford Center for Induced and Triggered Seismicity, was used to calculate the probability of slip on the identified fractures from a pore pressure perturbation by modeling Mohr-Coulomb slip, and to evaluate the effects of input parameter uncertainty on this calculation.

Key inputs for this evaluation include the orientations and magnitudes of S_V, S_{hmin}, and S_{Hmax} and observed pore pressures at the 4850 level at SURF: these are presented in Table 1.

Table 1: Input parameters for slip tendency analysis

Parameter	Input value	Source
S_V	41.8 MPa (6062 psi)	Estimated using reference depth of 1478 m (4850 feet) and stress-depth relation proposed by Pariseau (1986) for Homestake Mine (σ_v = 28.28 x). This value corresponds well with an estimate of σ_v using rock densities from Hart et al. (2014)
S_{hmin}	21.7 MPa (3147 psi)	Average value from kISMET measurements (Wang et al., 2017)
S_{Hmax}	34.0 MPa (4931 psi)	From wellbore breakout analysis (~0.8 to 0.9×S_V)
S_{Hmax} azimuth	85°	Mean hydraulic fracture azimuth determined from kISMET (Wang et al., 2017; as corrected in Ulrich et al., 2018)
Pore pressure	8.3 MPa (1200 psi)	Maximum expected reservoir pressure based on Horner analyses of borehole pressure buildup tests at SURF (Stetler, 2015)

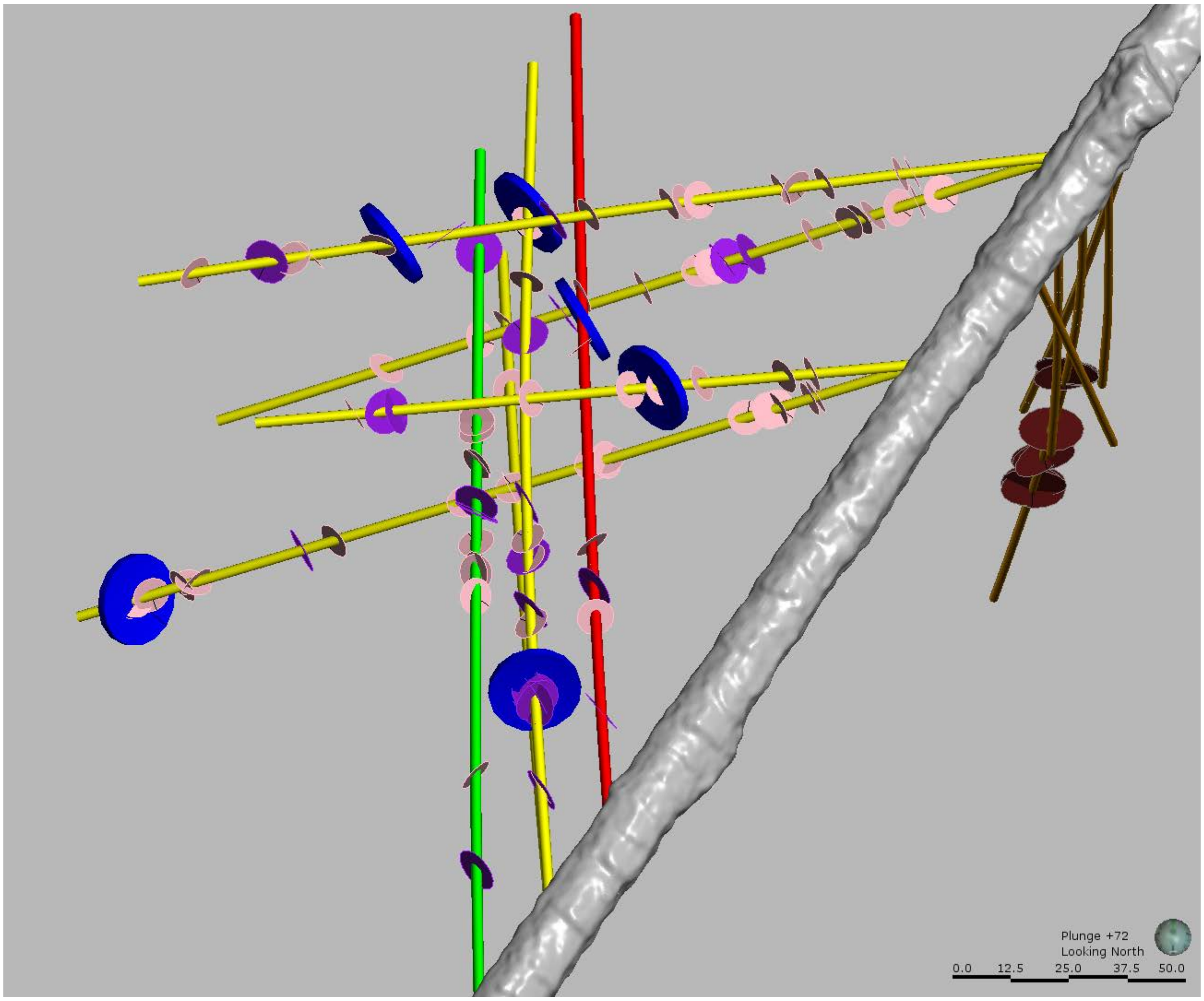

Figure 3: Leapfrog 3-D image (looking due north down at 72º) of EGS Collab Experiment 1 test bed with mapped fractures in boreholes from televiewer logs. Grey feature is the West Drift. Pink disks are quartz-filled fractures, purple disks are quartz open fractures, blue disks are open flowing fractures, and maroon disks are hydrofractures stimulated in kISMET-03. The green line is the injection borehole, the red line is the production borehole, and the yellow lines depict the monitoring boreholes. Brown lines represent the near-vertical kISMET holes. The entire 3D volume is within the Poorman Formation. Scale bar is in feet.

Analysis of the slip tendency of the mapped fractures at the Experiment 1 site was conducted using the calculated stress orientations and magnitudes listed in Table 1. Based on this analysis, the fractures (Figs. 4, 5) were grouped into three categories: high slip tendency (depicted in red); moderate slip tendency (depicted in yellow), and low slip tendency (depicted in green). The Mohr diagram shown in Fig. 5 represents the condition when the pore pressure = S_{hmin}; thus the red fractures are likely to have shear slip before a hydraulic fracture is created. Steeply dipping fractures with strikes near N60W and N60E (Fig. 5) would be optimally oriented for slip failure; a moderate increase in pore pressure would induce shear failure below the pressure needed to initiate a hydrofracture. Based on this analysis, a large number of fractures occur within the current Experiment 1 testbed that have high to moderate slip tendencies, including a flowing fracture feature that connects the E1-P and E1-OT boreholes.

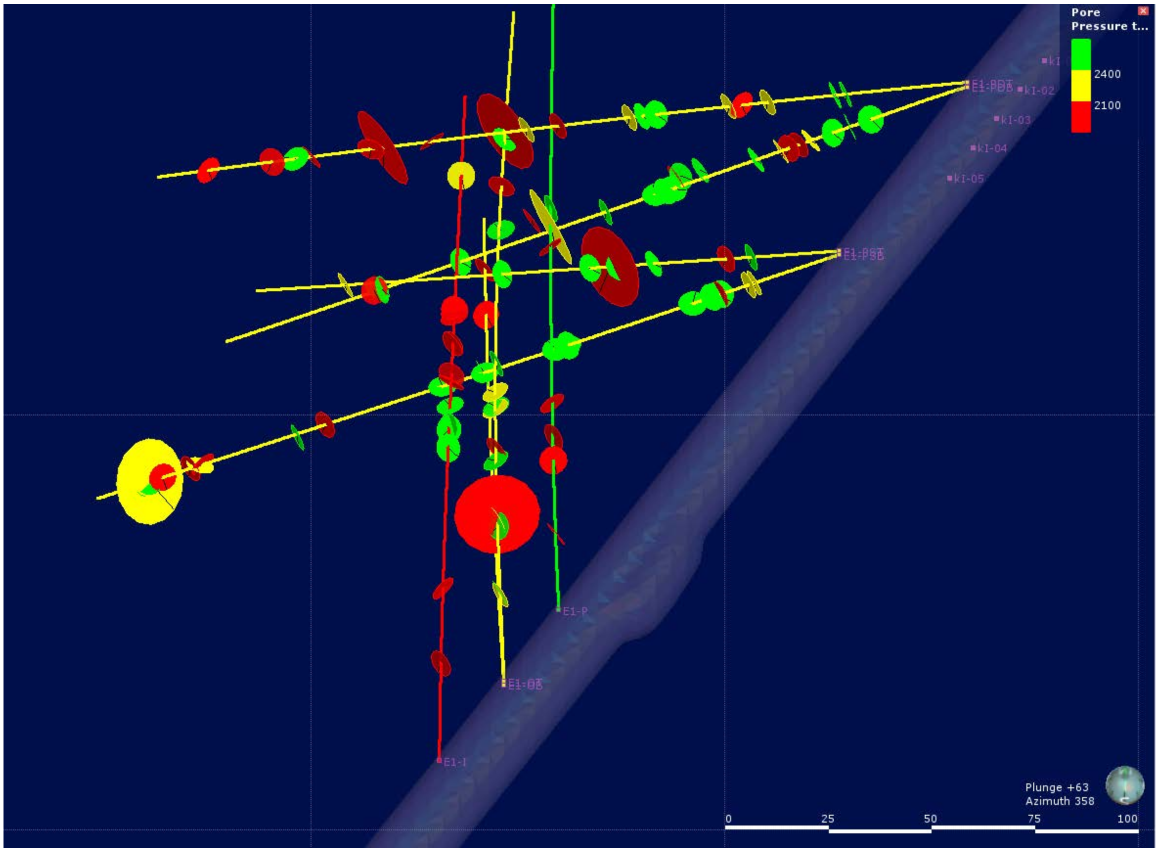

Figure 4: Fracture map of Experiment 1 site with fractures color-coded based on slip tendency. Red fractures have high slip tendency, yellow fractures have moderate slip tendency, and green fractures have low slip tendency. Larger discs represent fractures with observed flow. Scale is in feet.

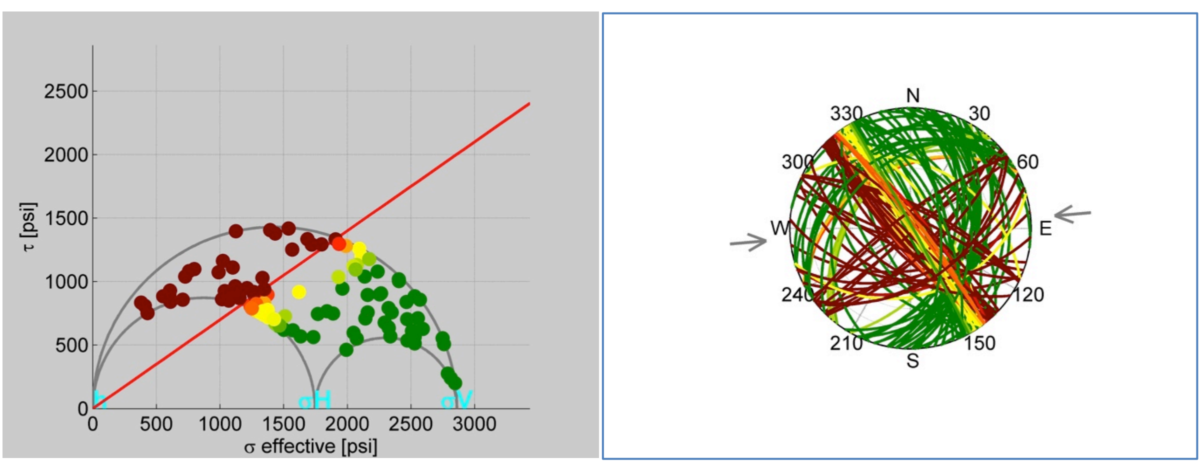

Figure 5: Mohr diagram constructed with the failure line starting from the S_{hmin} point, and depicting slip tendencies of different fracture orientations (left), and stereonet plot of mapped fracture planes from Experiment 1 (right) with color-coded slip tendencies (red – high slip tendency; yellow – moderate slip tendency; green – low slip tendency).

3.1.3 Fracture length and location constrained by hydraulic characterization

An important criterion for selecting natural fractures is having sufficient size and extent to connect two boreholes over a scale of approximately 10 m. Identifying such fractures involves the ability to find multiple intersections of the same fracture or feature in boreholes and on the drift wall. The locations and orientations of these intersections should be consistent with a single hydraulic feature connecting the multiple points. The integration of image logs, core logs, and flow observations allowed the development of a hydro-structural conceptual model, which is a model describing the conducting fracture network. Within the EGS Collab experiment to date these data have come from observations of (1) crossflow between boreholes during drilling, (2) crossflow while pressurizing one borehole and observing inflows with the downhole camera and other boreholes, (3) observations of flow on the drift walls, and (4) natural flows of long duration that imply large scale fracture connectivity (Roggenthen et al., 2018).

At least three prominent conductive fractures (Fig. 6) have been identified in the work that has been performed to date in the Experiment 1 testbed (Roggenthen et al., 2018). The largest of these is a complex fracture zone called the “weep zone”, as this feature is prominent on the drift walls in the Experiment 1 area near the E1-P wellhead. The weep zone is approximately 10 feet (3 m) in thickness. Along the drift wall there are a few damp spots but mostly the indication of flow is a buildup of a white, fluffy mineral (a form of sodium sulfate) derived from the evaporation of inflow by the ventilation system. The internal structure of the weep zone includes open fractures with terminated crystal coatings, breccia, and some vuggy porosity. The weep zone is very prominent in the core between 3 and 12 feet measured depth (1 and 4 m) in borehole E1-P, where it is only a few meters from the drift wall and lies behind the borehole’s casing. The weep zone also appears prominently in the monitoring borehole E1-OT between 40 and 52 feet (12 and 16 m) measured depth (Fig. 7). The zone is less prominent in the injection hole E1-I between 83 and 90 feet measured depth (25 and 27 m) and does not have an unambiguous intersection in any other boreholes. The orientation of the weep zone has a strike of approximately N50W and is subvertical.

The second prominent feature is based on observations of crossflow during drilling between the E1-P and E1-OT boreholes. Although the transmissivity of this feature has not been quantified, the transmissivity is quite large, but the absence of natural flows indicates that the fracture does not have connectivity to the mine-scale flow system. Flow testing subsequent to drilling showed that this fracture intersects E1-OT at a measured depth of 162 feet (49 m) and E1-P at a measured depth of 122 feet (37 m). The average orientation of this feature has a strike of N44W and is subvertical.

The post-drilling flow tests also indicated a connection between the injection hole E1-I and monitoring borehole E1-PDT. The flowing fracture in E1-PDT appears at a measured depth of 142 feet (43 m) and has a strike of N45W and a subvertical dip. The intersection location of this fracture with E1-I was not determined.

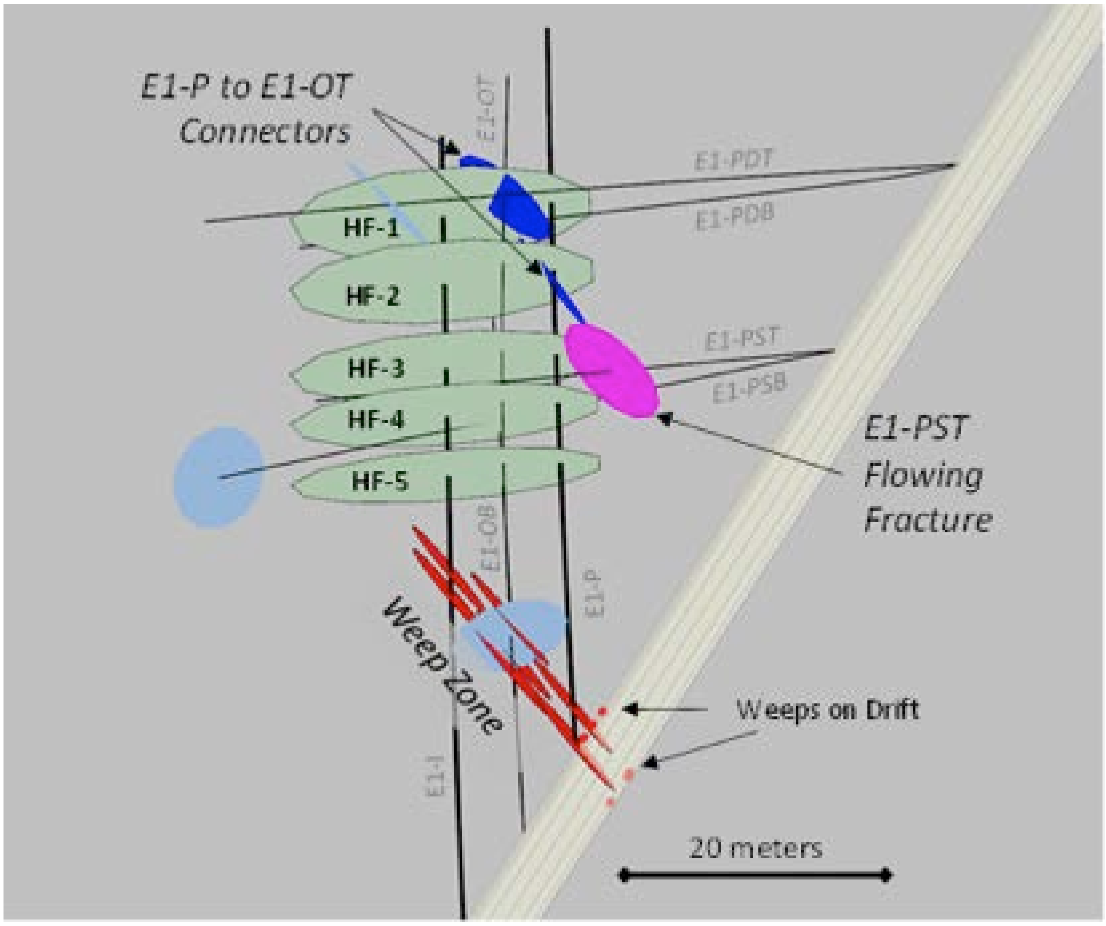

Figure 6: Hydrostructural model for EGS Collab Experiment 1 location. Red: Weep zone; Dark Blue: E1-P to E1-OT connecting fracture; Magenta: E1: PST flowing fracture; Light blue discs indicate additional observed minor flows. HF (green discs) are possible hydraulic fractures for Experiment 1. Except for the hydraulic fractures, the discs represent a fracture location on a borehole and its orientation. The size of the disc is only for purposes of visualization. A single fracture may be inferred from the alignment and common orientation of multiple fracture intersections in boreholes.

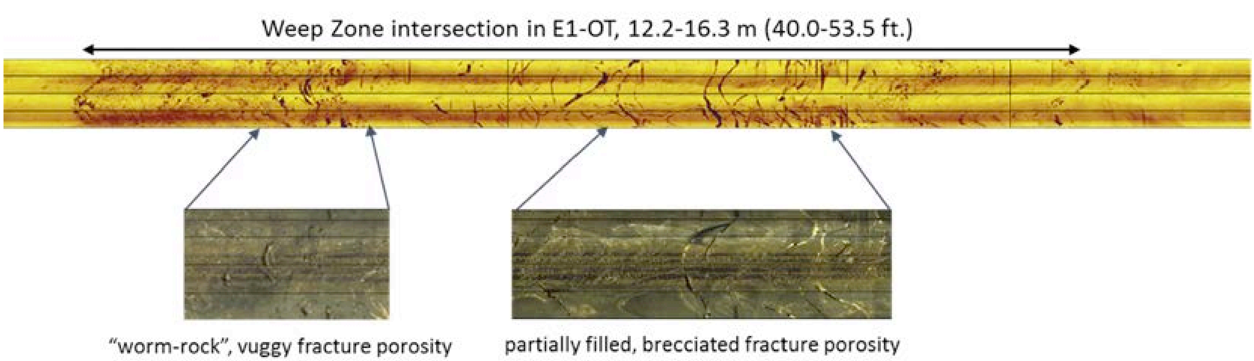

Figure 7: Acoustic televiewer log showing the trace of the fracture zone in borehole E1-OT associated with the weep zone. Although the zone is complexly fractured, the zone can be clearly correlated with a similar zone in the E1-P borehole based on similar textures and geometric alignment.

Finally, a fracture in E1-PST occurring at a measured depth of 55 feet (17 m) produced the only significant natural flows. These flows began at approximately 0.5 L per minute and continued for approximately 3 weeks before tapering off to near zero after about one month. The orientation of this fracture in the televiewer log had a strike of N45W and dip of 66 degrees to the southeast. This fracture does not have a clear intersection in any other boreholes, but clearly has a significant extent based on the duration of its natural inflow.

3.1.4 Existing infrastructure

The Experiment 1 site on the West Drift of the 4850 level has excellent logistical support. This location has all of the non-geologic features (wide drift, rail service, ground support, power, water, internet) needed for conducting the activities proposed for Experiment 2. This would result in significant time and cost savings if the second experiment were to be sited in this location.

3.2 Disadvantages of the West Drift location on the 4850 level

There are several concerns involving siting Experiment 2 at or near the current Experiment 1 location. First, there is a possibility that the West Drift location on the 4850 level may not be accessible beginning in 2020, upon when major blasting and excavation operations are scheduled to begin for the construction of the Long Baseline Neutrino Facility, which will be located SE of Governor's Corner. Another concern is that many of the natural fractures that have a high slip tendency are oriented nearly perpendicular to the West Drift (Figs. 4, 6), so that it would be challenging to have both production and injection boreholes intersect such features and still have an adequate safety margin so that these fractures do not propagate into the drift; a natural example of this is the weep zone that intersects the drift near the production borehole (Roggenthen et al., 2018). A final concern is that the hydrofractures generated during Experiment 1 might create a series of permeable flow paths that could intersect many of these prospective fractures, thus creating transmissive leak-off zones that would retard shear stimulation. However, shifting the location of Experiment 2 to the other side of the drift (to the east) or in the direction of Governor's Corner (to the south) could alleviate this last concern.

4. Evaluation of 4100 level candidate sites

During a recent reconnaissance trip to the 4100 level, a number of potential locations were visited and two potential sites for hosting Experiment 2 were identified (Fig. 8). The first of these sites is located about 200 feet (60 m) south of the Yates Shaft, at the site of a former battery charging alcove within the Yates amphibolite. The second site is located on the WNW-trending cross drift between the Ross Shaft and the 3 Winze within the Poorman Formation, where three small cutouts are present.

There are some general aspects of both of these sites that make these locations on the 4100 worthy of consideration. The 4100 level has minimal use by other scientists at SURF, so that the EGS Collab team would be able to have access to this level throughout the duration of the project. This location is at a different depth, and would provide different relative stress conditions (shallower depths would result in a smaller magnitude S_V). There are also some existing alcoves along this drift that could be used for siting drilling and experimental activities. The level does have functional rail service between the Yates and Ross Shafts (thus covering both sites under consideration), and there is limited power and internet available in selected locations. The sump located just north of the Yates Shaft is the main source of water for operations on the 4850 – presumably, this sump could also supply water for work conducted on the 4100.

Both locations on the 4100 level have some inherent drawbacks. The first of these is that this level is much less characterized geologically than the site on the 4850 level. No stress measurements have been made on this level. There are Homestake maps of the drift geology of the 4100 level at 1”:50’ and 1”:200’ scales, and Lisenbee and Terry (2009) conducted some limited mapping of the orientation and location of fractures exposed along the drift walls on this level. However, additional geologic characterization of the 4100 would be needed to confirm that these sites meet the geologic requirements for Experiment 2.

Another major challenge to working on the 4100 level is that significant upgrades would be required to provide the needed logistical support for the project. Additional ground support would need to be installed on this level, and the site would need improvements to water, power, and internet services. The drifts on the 4100 level are much smaller than the West Drift Experiment 1 site on the 4850 level (Fig. 8), and existing alcoves would need to be expanded to provide the space needed for operating a drill rig and installing all of the equipment needed for the simulation, flow and monitoring components of the experiment. Additional site-specific advantages and disadvantages of these two sites are described below.

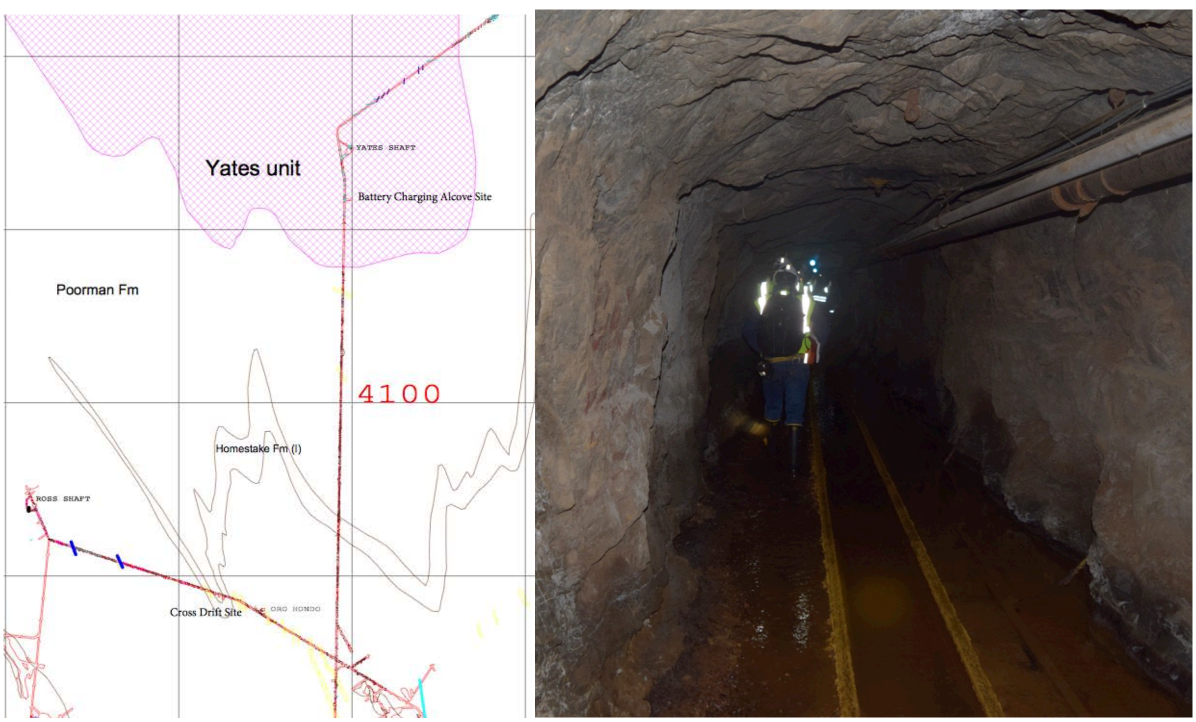

Figure 8: Geologic map of the 4100 level (left) with two potential locations shown (Battery Charging Alcove site and Cross Drift site). The drifts are indicated by orange lines, the yellow features are Tertiary rhyolite dikes, and the Yates amphibolite is depicted by the purple hachured region. The grids are 1000’ apart. Drifts on the 4100 level are smaller (typically ~7×7 feet) and have minimal ground support in some locations (right).

4.1 Attributes of the Battery Charging Alcove location on the 4100 level

There are a number of factors favorable to siting Experiment 2 on the 4100 level in the battery charging alcove that is located about 200 feet south of the Yates Shaft. This site is located within the Yates amphibolite, a fine-grained hornblende plagioclase schist (Caddey et al., 1991) that is interpreted to have originated as tholeiitic basaltic flows, tuffs, and volcaniclastic sediments – this unit forms the base of the Poorman Formation. This rock is not as foliated as the Poorman phyllite, and is likely to be more representative of potential EGS host rocks. The quartz-rich zones that were problematic to drilling at the Experiment 1 site do not appear to be present within the Yates. Some transmissive fractures that were identified by surficial sulfate mineral precipitation were observed in the vicinity of this location. Lisenbee and Terry (2009) measured fracture and foliation orientations in the Yates amphibolite in exposures near this location – some of these fractures appear to be oriented favorably for shear stimulation if it is assumed that this location has similar stress orientations to those observed on the 4850 level. This site has a fairly large alcove that extends about 10 m east of the main drift – it would need to be expanded to accommodate the injection and production boreholes. Monitoring boreholes could be located off of the main north-south drift. This location has 110V power and internet that were installed for a now decommissioned microgravity station. Because this location is near the Yates shaft, the cost to run additional power, internet, and other support services should not be excessive. This site is far enough from a sump located north of the Yates Shaft so that conducting hydroshear experiments here should not pose a hazard to the integrity of the water storage system.

4.2 Attributes of the Cross Drift location on the 4100 level

The Cross Drift location between the Ross Shaft and the 3 Winze appears not to be as favorable as the battery charging alcove location described above. There are a total of three cutouts on the south side of this drift: one of these was the site for a now decommissioned experiment where point loading tests were made (Gage et al., 2014). Some site characterization work conducted as part of this earlier study measured orientations of rock foliation (044/50SE) and four joint sets (044/50SE, 161/86W, 075/87 SE, and 205/39NW) at this location, and also carried out mechanical testing of Poorman core samples from this location (Gage et al., 2014). The geology of this location is quite complex – a series of rhyolite dikes are exposed nearby to the east, along with a section of the quartz-rich Homestake Formation. Active weeps are observed in fractures in the Poorman that are parallel to the rhyolite dikes near the intrusive contact. If the existing cutouts were to be used for hosting the injection and production wells for the new test bed, this location appears to be too far to the west to be able to easily utilize the NS-oriented drift to the Yates Shaft for siting monitoring holes. This site is fairly distant from the Yates and Ross Shafts, so the cost of providing necessary power, internet, and other support services would be significantly greater than the location near the Yates Shaft. Finally, the drift near the crossover may need quite a bit of ground support for regular access to this location. All of this work would require many months of time and significant investments to bring this site up to the conditions needed to successfully build a test bed for Experiment 2.

5. Conclusions

Based on our initial evaluation of sites on the 4850 and 4100 levels at SURF, the current location of Experiment 1 on the 4850 level appears to be an attractive candidate for conducting

Experiment 2. This site is well characterized, has natural fractures that are well oriented for slip, and has all of the infrastructure needed to conduct the stimulation and flow tests planned for Experiment 2. However, an alternative site within the Yates amphibolite on the 4100 level (the battery charging alcove) is also worthy of consideration. Additional field evaluations of both of these sites, with a focus on fractures, as well as evaluation of site-specific logistical requirements, are recommended prior to finalizing the site selection. This work would help in the design of a test bed that would identify the prospective natural fractures that would be stimulated and come up with an optimal borehole configuration for stimulation, production, and monitoring, similar to what was done for Experiment 1 (Morris et al., 2018).

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