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ABSTRACT: The EGS Collab project is focused on understanding and predicting permeability enhancement and evolution in crystalline rocks. To accomplish this, the project is creating 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 part of the site characterization effort for the first experimental test bed, our team has worked on mapping the distribution, orientation, and nature of open and healed fractures exposed along the drift wall and within the eight bore holes drilled for this test bed. The fractures have been characterized through detailed description of continuous cores obtained from these boreholes, evaluation of televiewer logs, and mapping of fractures and seeps exposed along the drift wall. The fracture data are being compiled and interpreted for slip and dilation tendencies, and will be incorporated into coupled-process geomechanical flow and transport models to better constrain the planned flow and tracer tests.

INTRODUCTION

The goal of the EGS Collab project (Kneafsey et al., 2018) is to establish a suite of intermediate-scale (~10- 20 m) field test beds to host stimulation and interwell flow tests that will provide improved understanding of fracture stimulation methods, resulting fracture geometries, and processes that control heat transfer between rock and stimulated fractures for Enhanced Geothermal Systems (EGS). Our diverse team recently developed the first experimental test bed for conducting these experiments at the Sanford Underground Research Facility (SURF), the former Homestake gold mine, located in Lead, SD. Our experimental site is located on the 4850 level (1478 m below the surface) of SURF in the Precambrian Poorman Formation phyllite. The test bed consists of a stimulation/injection borehole, a production borehole, and six monitoring boreholes (Fig. 1). The borehole layout (Morris et al., 2018) was designed so that the axes of the injection and production boreholes are approximately parallel to Shmin, which will cause hydraulic fractures to be generated perpendicular to the boreholes. In this initial test bed, we will perform well-controlled and intensely monitored in situ experiments focused on creating a series of hydrofractures that connect the injection and production boreholes; these fractures will be used to evaluate fluid flow and heat transfer. However, the created hydrofractures may intersect permeable natural fractures, which may result in the cross well flow tests being in a fracture network rather than a single fracture. Thus, it is important to understand the distribution, orientation, and nature of existing fractures in the test bed prior to the hydraulic fracture stimulation and flow test experiments.

The testing and evaluation of models are key goals of the EGS Collab experiments. 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. 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.

The objective of this paper is to provide a brief description of the natural fracture system at the EGS Collab site based on initial characterization studies, with a focus on the orientations of the fracture sets. This paper complements the work of Roggenthen et al. (2018) on other aspects of the natural fracture system.

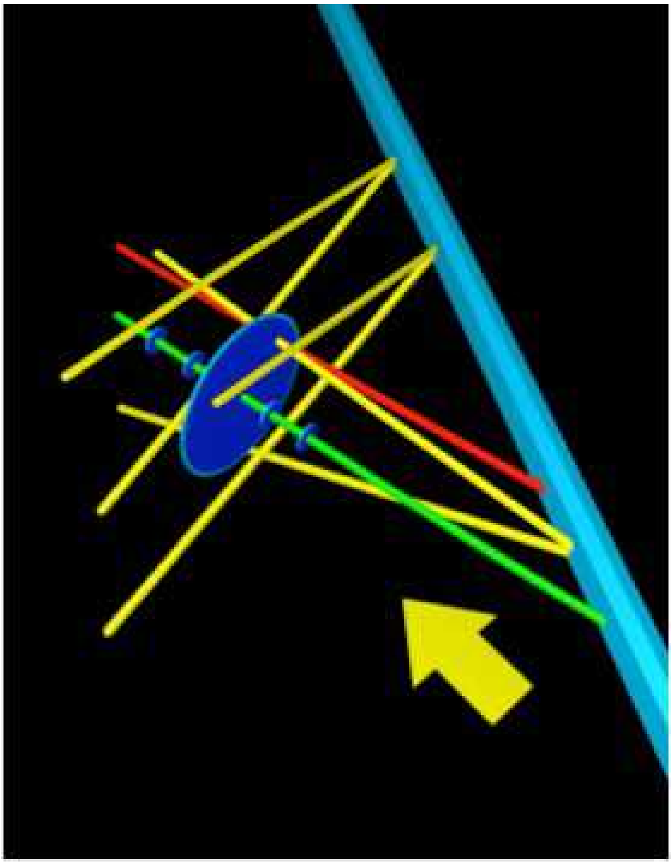

Fig. 1. Layout of the EGS Collab borehole test bed developed on the 4850 level (1478 m below ground surface) for fracture stimulation and flow experiments. The long blue feature is the West Drift tunnel. Boreholes are ~60m in length. The green borehole is the stimulation/injection borehole, the red borehole is the production borehole, and the yellow boreholes will contain an array of sensors to monitor the experiments. The yellow arrow indicates north. The blue discs represent zones in the stimulation well that were notched to facilitate hydrofracturing in the design direction, which is perpendicular to Shmin; the larger blue disc is a conceptual fracture trajectory from a notched section of the borehole.

PREVIOUS GEOLOGIC AND STRUCTURAL STUDIES

Geologic Setting

The SURF facility occupies the former Homestake gold mine, located in the Black Hills of South Dakota in the town of Lead. The gold deposit is associated with sulfide mineralization in the Homestake Formation, an early Proterozoic banded iron formation (Caddy et al., 1991; Frei et al., 2009). This is part of a sequence of metasedimentary and metavolcanic rocks that were deposited about 2.0 Ga. These units underwent metamorphism associated with granitic intrusion at about 1.71 Ga (Frei et al., 2009). The rocks also underwent deformation during this orogenic event, resulting in the generation of tight isoclinal folds and shearing. This area was subsequently uplifted to form the Black Hills at about 530 Ma. The area was the site of early Tertiary alkalic volcanism, expressed by numerous trachytic dikes and sills that cut the early Proterozoic metamorphic sequence.

The test bed for Experiment 1 of the EGS Collab project (Fig. 2) is located in the oldest unit of this sequence, 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; this formation also contains the Yates member, consisting of a hornblende-biotite amphibolite. Just to the north of the EGS Collab test bed is a series of discontinuous aphanitic Tertiary rhyolite dikes, which trend ~N20W and dip steeply to the NE – these dikes are prominently exposed in the Open Cut at the surface (Fig. 3).

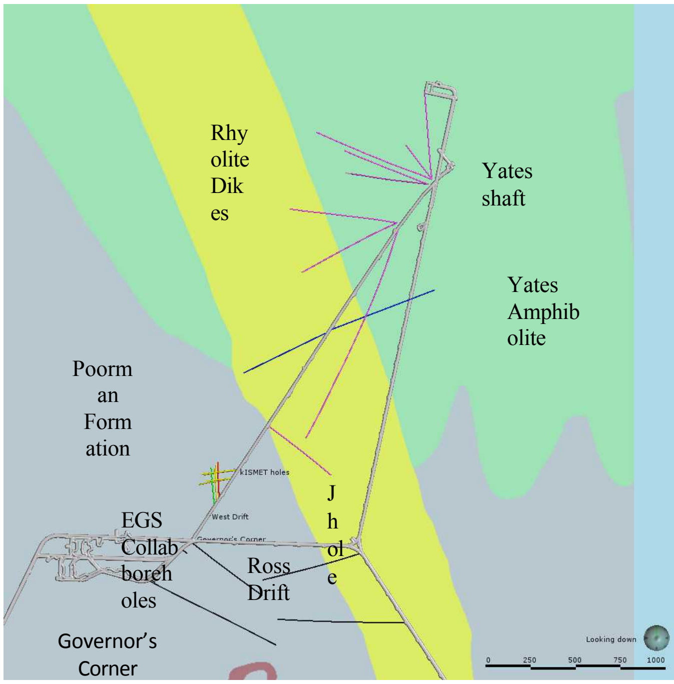

Fig. 2. Geologic map of SURF on the 4850 level (1478 m below ground surface) for the region between the Yates shaft and Governor’s Corner. Zone of Tertiary rhyolite dikes is depicted schematically – the dike swarm is not continuous. The different groups of boreholes are color-coded: Purple: Deep Underground Science and Engineering Laboratory (DUSEL); Black: Long Baseline Neutrino Facility (LBNF); Blue: Homestake; Orange: kISMET; Green: E1-I, Red: E1-P, Yellow: E1-OT, -OB, -PSB, -PST, -PDB, and -PDT EGS Collab boreholes. Map created using Leapfrog software with data inputs from the Homestake Vulcan geologic database and borehole information from this study.

Fig. 3. Tertiary rhyolite dikes intruded into the Poorman Formation at the Open Cut, Lead, SD.

Previous Structural Studies

A number of geologic and geotechnical studies have been conducted at the SURF site that provide important details surrounding the structural setting. Caddey et al. (1991) describe two major deformational events that occurred during the Early Proterozoic. The first event (D1a), consisted of regional shearing and folding, then a flattening event, followed by sheath (conical) folding with axial fabric development and stretching lineation, and concluding with ductile shearing with planar mylonitic fabric. The second event (D1b) is characterized by upright folding with vertical plane foliation, ductile-brittle shearing with ore mineralization, followed by post-ore brittle shearing and crenulation/kink fabric. The most prominent structural feature associated with these events is a series of tight anticlines and synclines – the fold axis of the Lead Anticline, which plunges to the SSE, is located just to the east of the Experiment 1 site. Quartz bodies occur mainly as pods with diameters of one meter or less and thin veins occur as well.

Several geotechnical studies were conducted on the 4850 level of Homestake that provide additional detailed information on structural features that are relevant to the EGS Collab site. A study by Lachel Felice and Associates (2009) describe the orientations of mapped fractures along the West Drift. In the area near the EGS Collab site, a plot of joint, bedding, and fault orientations measured in the drift (described as structural domain 2E) indicates that the main cluster of structural features (consisting mainly of joints) is oriented N73W, dipping 78 degrees to the SW. A structural study conducted by Lisenbee and Terry (2009) notes that the crest of the Lead Anticline is located near the Yates shaft, with its axis plunging 24 degrees to the SE. The Poorman Formation, typically a graphite-sericite-biotite phyllite, is folded on a variety of scales, ranging from small crenulations to mesoscopic folds, and contains massive quartz bands. These investigators also noted the presence of vertical fracture sets southwest of Governor's Corner, with strikes of N68E and N30W.

Golder Associates (2010) conducted additional structural characterization work in this area. The portion of their study area that relates to the EGS Collab site was defined as structural domain II – based on characterization of structures within the nearby J borehole (see Fig. 2), two joint sets were identified: a dominant set that strikes NE and dips at an angle of ~45 degrees to the SE, and a second set in the Poorman phyllite that strikes west and has a subvertical dip.
Extensive structural characterization of the Long Baseline Neutrino Facility (LBNF) area along the Ross Drift was conducted by Arup (2015). This work included mapping of joints, fractures and foliation along the drift and in the LBNF boreholes (see Fig. 2 for location). This study identified four structural domains based on the orientation and style of deformation. Domain 3, which projects into the EGS Collab area, is characterized by planar foliation, minor joint veins, and consistent rock mass quality (Arup, 2015). The foliation in this domain has a NW strike and dips around 65 degrees to the NE. The main joint set was observed to be parallel to the foliation. More details on these observations are presented in Figs. 7 and 9.

Previous Stress Measurements

A series of stress measurements were previously conducted on the SURF 4850 level in the kISMET project boreholes (Oldenburg et al., 2016; 2017; Wang et al., 2017), which are near the EGS Collab site (Fig. 4). This project used a central borehole and four closely spaced monitoring boreholes, all subvertical in orientation, to conduct hydraulic fracturing experiments to characterize the stress field, understand the effects of rock fabric on fracturing, and gain experience in monitoring using geophysical methods. Stress measurements obtained through hydraulic fracturing experiments (Fig. 5) indicated that the minimum horizontal stress at kISMET averages 21.7 MPa (3146 psi) and trends approximately N-S (azimuth of 355 degrees) with a slight plunge of 9.3 degrees to the NNW (note that these values have been corrected slightly from previously published values (Wang et al., 2017) to correct for the slight deviation from verticality for the central borehole where the minifracs were conducted). The hydraulic fractures that were generated crosscut foliation. Very few open fractures were observed in the 300 m of core obtained from the near-vertical kISMET boreholes.

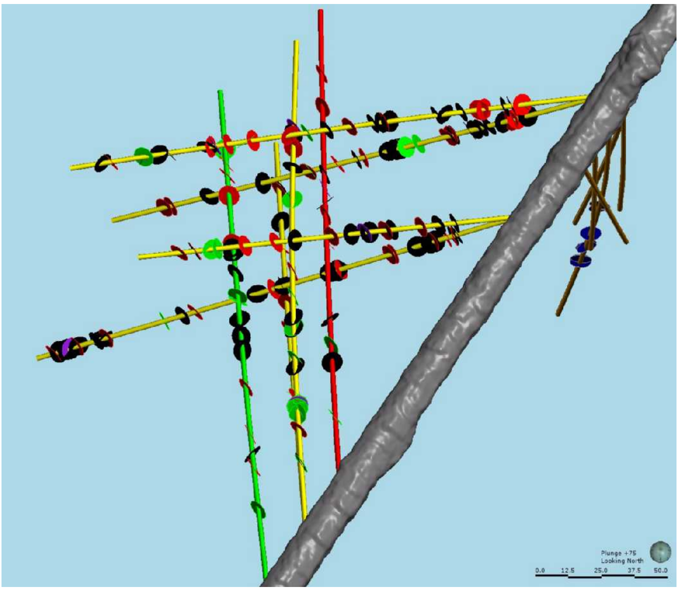

Fig. 4. Leapfrog 3-D image (looking due north down at 75º) of EGS Collab Experiment 1 test bed with mapped fractures in boreholes from televiewer logs. Grey feature is West Drift. Red disks represent foliation, green disks are open quartz- lined fractures, black disks are closed quartz veins, and open flowing fractures are purple disks. The green line is the injection borehole, the red line is the production borehole, and the yellow lines depict the monitoring boreholes. Orange lines and blue disks represent near-vertical kISMET holes and stimulation fractures, respectively. The entire 3D volume is within the Poorman Formation.

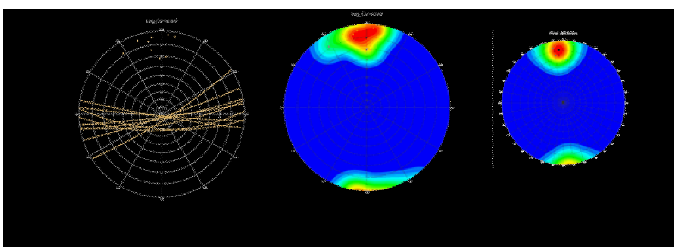

Fig. 5. Plotted corrected orientations of fractures generated in the kISMET hydraulic fracturing experiments.

Additional constraints on the stress regime were obtained by examination of borehole breakouts in the neighboring J borehole, which was drilled for previous physics-experiment cavern design. This hole, which has a trend of 128° and upward plunge of 2.4° (Oldenburg et al., 2016) had subhorizontal breakouts, suggesting a vertical maximum principal stress. On the other hand, breakouts are absent from both the kISMET and EGS Collab boreholes, despite the EGS Collab E-W holes being optimally oriented for breakouts. This difference may reflect greater stress complexity in the J borehole area, which may be related to its location in a zone of stiff rhyolite dikes.

NATURAL FRACTURES IN THE EGS COLLAB TEST BED

Fracture Characterization Techniques

A number of different methods were employed to describe and characterize natural fractures in the EGS Collab test bed. These methods include:

- Mapping of fractures and weep zones in the drift
- Mapping of fractures and veins in borehole core samples
- Determination of fracture orientations and locations through acoustic and optical televiewer logs of the boreholes
- Observation of flowing fractures using a sewer camera in the boreholes

The compiled fracture location and orientation data have been incorporated into a 3D geologic model of our site using Leapfrog software (Fig. 4). This geologic model will serve to inform coupled process numerical simulations used to design and evaluate the results of the hydraulic fracturing and flow and heat transfer experiments that will be conducted in the test bed.

The companion paper by Roggenthen, Doe et al. (2018) provides details on the mapping and characterization of fractures in the drifts and cores as well as a hydrostructural model of major water-conducting features. This paper concentrates on the fracture orientation data obtained from the televiewer logs. Examples from televiewer data from one of the boreholes are presented in the following subsection.

Televiewer Log Results

Acoustic and optical televiewer logs were run in all of the test bed boreholes to help identify foliation, vein, and fracture locations and orientations (Fig. 6).


Fig. 6. Televiewer logging of E1-PSB borehole.

The boreholes were flushed after drilling to remove drilling fluid, and in some instances, the boreholes were further flushed and cleaned out using a chimney sweep brush to improve image quality. Typically, better quality images were obtained from the acoustic televiewer log data. Fracture, vein and foliation features were identified in the log images, and the orientations of these features were corrected using the surveyed orientations of the boreholes obtained from gyro and deviation logs.

The following figures (Figs. 7-10) show the range of orientations observed for fractures and foliation in the EGS boreholes as determined from the acoustic borehole televiewer logs. Note that there is good agreement with the orientation of similar features from the corresponding zone (Domain 3) of the LBNF structural study (Arup, 2015).

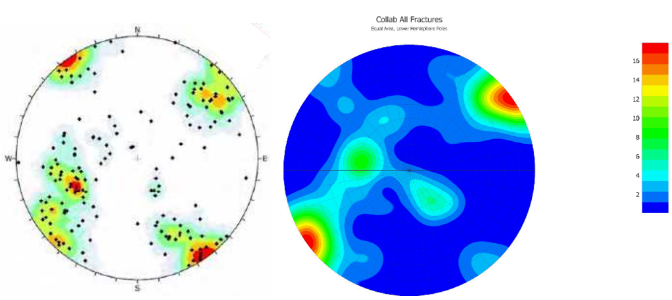

Fig. 7. Equal area lower hemisphere stereonet projection of poles to planes for fracture orientations identified from Domain 3 (Arup, 2015) of the LBNF study area (left) and identified from televiewer logs from the EGS Collab boreholes (right).

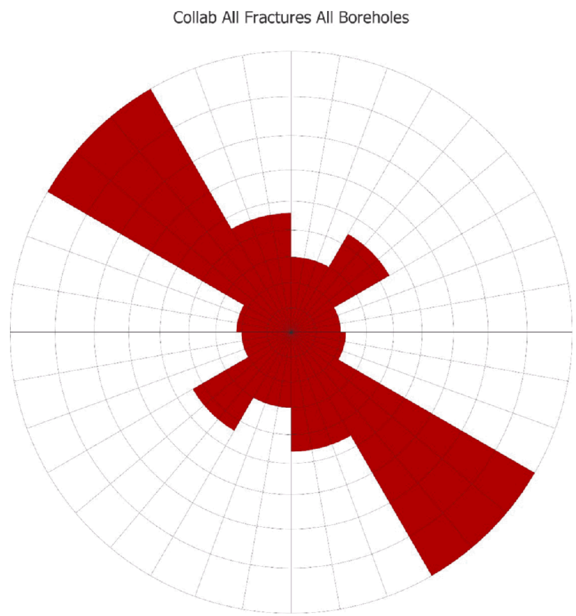

Fig. 8. Rose diagram of strike (azimuth) orientations of fractures from EGS Collab boreholes as determined from televiewer logs.

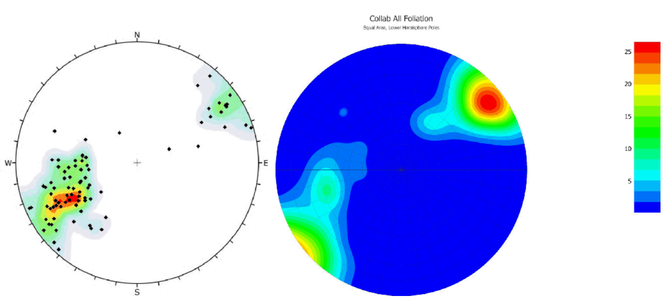

Fig. 9. Equal area lower hemisphere stereonet projection of poles to planes for foliation orientations identified from Domain 3 (Arup, 2015) of the LBNF study area (left) and televiewer logs from the EGS Collab boreholes (right).

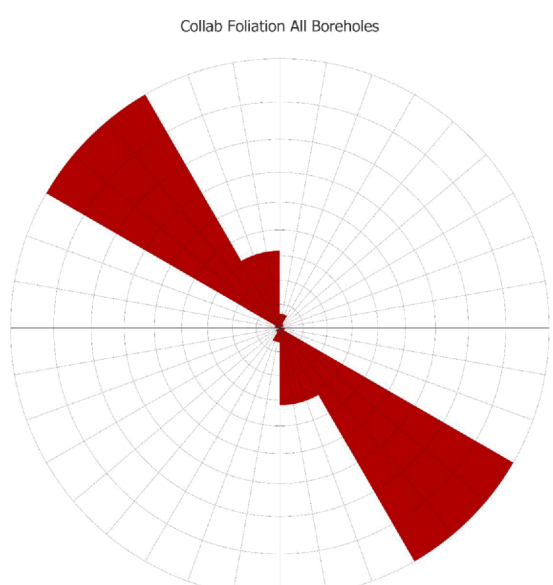

Fig. 10. Rose diagram of strike (azimuth) orientations of foliations from EGS Collab boreholes as determined from televiewer logs.

General Observations

Several observations can be made based on our preliminary analysis of these logs and the other fracture characterization methods described above.

- The foliation orientation observed from the borehole televiewer images (striking N30W to N60W with steep dips) is similar to the foliation strike reported by the Vulcan database for this area, and for foliation observed in the nearby structural Domain 3 from the Arup study.
- For the EGS Collab boreholes, there is a dominant fracture set that has the same strike orientation as the foliation (N30W to N60W), similar to what was observed in the Arup study. There is a secondary orthogonal fracture set that strikes N30E to N60E. These orientations are quite similar the fracture measurements obtained from the ARUP study.
- Most of the fractures are steeply dipping (this may account for why so few fractures were encountered in the near-vertical kISMET boreholes).
- In contrast to the nearby J borehole, no borehole breakouts were observed. One potential explanation is that the local stress regime near the J hole has been perturbed by the intrusion of the Tertiary rhyolite dike swarm. Borehole breakouts were also not observed in the nearby LBNF boreholes.
- Zones of quartz pods were encountered in a number of the boreholes. These features, which were almost completely absent in the kISMET boreholes, ranged in thickness from a few centimeters to more than a meter. These very hard features caused much slower drilling rates.
- Most fractures were not open, permeable features. However, several fractures were observed that provide hydraulic connectivity between boreholes, and also appear to be linked to weep zones in the drift (see Roggenthen et al., 2018 for more details).

FUTURE ACTIVITIES

The mapping and characterization of natural fractures at the EGS Collab Experiment 1 site has two main purposes. The first is to identify natural fractures that might be intersected by the created hydrofractures that are designed to connect the injection and production wells for flow experiments. Natural fractures could interact with the hydrofractures in two ways: 1) they could serve to provide a quick connection to the production well, which would facilitate the flow experiments, but would complicate their modeling, or 2) they could cause fluid leak off during hydrofracturing, such that the hydrofracture does not reach the production well. Thus, prior knowledge of the presence and orientation of fractures in the test bed is important in siting the hydrofracture initiation zones in areas that are less likely to intersect transmissive fractures.

The second interest in the presence of natural fractures at the EGS Collab site is that these might provide a prospective test bed for Experiment 2, which is designed to stimulate a natural fracture via hydroshearing. Knowing the location, orientation, and extent of natural fractures would permit these features to be evaluated for slip tendency relative to the measured stress field (e.g., Siler et al., 2016). Finding a long, optimally oriented natural fracture within or near the current test bed could help in the identification of an appropriate site for conducting the planned hydroshear experiments during the next phase of this project. We will present more detailed analysis of the natural fractures that will use the stress orientations obtained from the kISMET study to determine the slip tendency for different groups of fracture orientations.

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