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Distributed Fiber-Optic Sensing Deployment in a Deep EGS Production Well at Utah FORGE: Preliminary Results and Lessons Learned

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ABSTRACT

Characterizing and monitoring the locations, connected geometry, and hydromechanical response of subsurface fracture networks is a crucial step in efficiently developing enhanced geothermal systems (EGS). Unfortunately, EGS reservoirs, dominated by high temperatures and corrosive brines, are a hostile environment for classical point sensors most useful in these monitoring tasks; seismic sensors in particular have a poor track record during intermediate and long duration studies in geothermal reservoirs. Full characterization of fracture networks requires coupled thermal and geodetic (e.g. strain) measurements at depth to effectively understand both the creation and dynamic behavior of fractures during flow. High temperature distributed fiber optic sensing (DFOS) systems present one potential solution to these challenges in the context of EGS. We present initial results from deployment of an integrated DFOS system at the Utah FORGE facility in well 16B(78)-32, as part of the Fiber Optic Geophysical Monitoring Of Reservoir Evolution (FOGMORE@FORGE) project. This well is the production well in the Utah FORGE EGS doublet. The DFOS system was designed to measure microseismic activity (DAS), record timelapse VSP surveys (DAS), temperature during production (DTS), and fracture-associated strain (DSS and LF-DAS). The sensing cable was designed to continuously survive temperatures in excess of 265 C through use of a rugged nickel alloy sheath (A825), high-temperature polymer buffers (PFA), and polyimide-coated fibers (2xSM, 2xMM, 1 engineered fiber). The cable and interrogator units were installed during July of 2023 and the deepest section equilibrated at ~235 C; the system was utilized during the 2023 stimulation and flow test, during periods of passive recording, and during the April 2024 stimulation experiment before failing due to fluid intrusion. We will present results from the system design phase, installation, commissioning, and stimulation/circulation experiments. A variety of interesting data streams were recovered during the 2024 stimulation which, while not fully analyzed, have helped to constrain the induced fracture geometry at depth. We will conclude with a discussion of some lessons learned during development of the DFOS deployment at Utah FORGE.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) relies on creating engineered fracture systems to transform hot, but initially impermeable, formations into producible resources using a circulating working fluid. Several recent successful EGS efforts including those executed at Blue Mountain, NV, Cape Station, UT (Norbeck et al. 2024), and at Utah FORGE (e.g. England et al. 2025) have modified and deployed stimulation techniques developed in the unconventional sector including hydraulic fracturing, multi-lateral completions, and the use of proppants. While both experiments were successful and generated commercial flow rates, a key question at these and future sites will be the geometry, connectivity, permeability, and long-term performance of such engineered fracture network in hot hard rock environments. Information on the fracture network will then help inform crucial engineering decisions including the position and completion of offset wells, spacing of production pads, and future completion strategies. A related question of significance is the interaction of induced hydraulic fractures with pre-existing fracture and faults, particularly pore pressure alteration and potential reactivation, processes of relevance to induced seismicity mitigation.

In lower temperature environments, many constraints on fracture geometry and connectivity can be obtained from downhole geophysical observations including microseismic array measurements, repeat well logging, permanent pressure/temperature gauges, and recently a suite of distributed fiber-optic sensing (DFOS) measurements including distributed acoustic, temperature, and strain sensing (DAS, DTS, and DSS respectively, [Raterman et al. 2020]). DAS in particular has significantly advanced our understanding of fracture dynamics by providing a combination of high-resolution in-reservoir microseismic information and low-frequency strain data (LF-DAS) to better constrain fracture hit locations (Jin & Roy 2017) and dynamics. Unfortunately, the EGS environment presents a host of challenges for deploying and utilizing downhole geophysical sensors including high temperatures (~230°C in our case), high pressures, and corrosive brines. For systems deployed in a campaign context (e.g. logging tools) temporary cooling of wells through fluid injection remains a possibility and instrumentation is only exposed for a fixed time duration. However, permanent behind-casing sensing systems are exposed to these conditions for an indefinite period, making downhole sensing using solid state components difficult. An additional challenge for instrumentation installed in wells undergoing hydraulic fracturing is mechanical damage due to induced fractures during stimulation.

We present initial results from deployment of an integrated DFOS system at the Utah FORGE facility in well 16B(78)-32, as part of the Fiber Optic Geophysical Monitoring Of Reservoir Evolution (FOGMORE@FORGE) project. As part of this project we are attempting to develop an end-to-end approach to utilize permanent fiber-optic cables and DFOS measurements to better constrain the geometry, compliance, and hydraulic connectivity of engineered fractures in an EGS environment. As mentioned, the project was conducted at the Frontier Observatory for Research in Geothermal Energy (Utah FORGE), an underground laboratory sponsored by the Department of Energy for developing, testing, and accelerating breakthroughs in EGS technologies (Moore et al. 2019). The Utah FORGE facility is located near Milford in Beaver County, Utah, on the western flank of the Mineral Mountains. The geothermal reservoir is dominated by hot (>175°C) crystalline granitic rocks, covered with alluvial fill. The reservoir is tight, with low porosity and permeability; there is no evidence of modern hydrothermal fluid movement. Figure 1A depicts the location of the Utah FORGE site with respect to Milford and the Mineral Mountains while Figure 1B shows the approximate locations of the wells discussed including the 16A/16B doublet and 78B-32 which will be discussed in this paper.

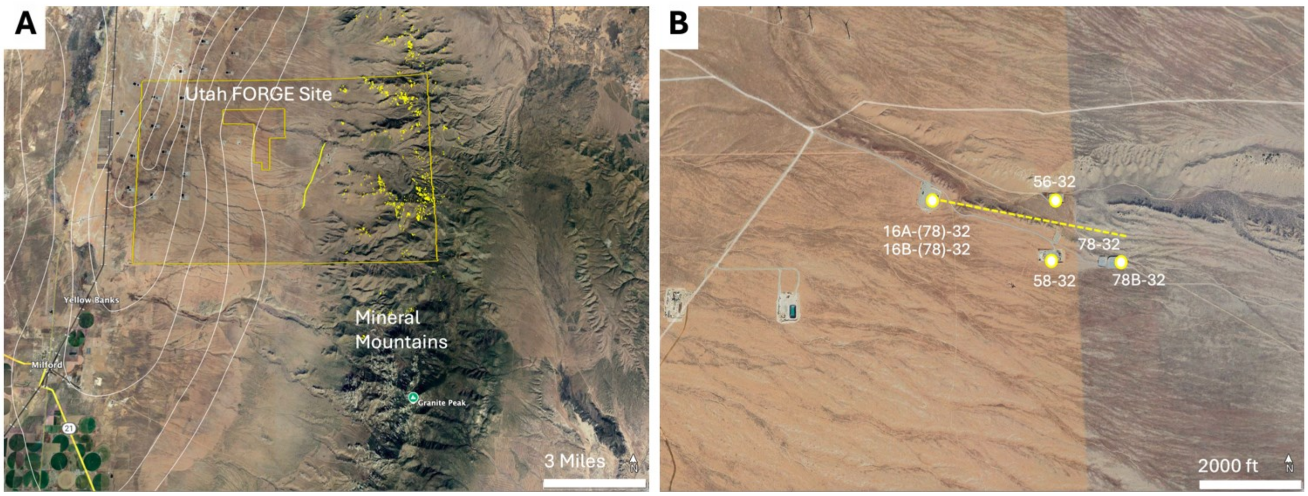

Figure 1: Experimental setting: Panel A shows the location of the Utah FORGE site with respect to Milford and the Mineral Mountains. White contours indicate basin depth and orientation. Panel B shows the wells mentioned in this paper with the dashed yellow line showing the approximate trajectory of the lateral sections of 16A and 16B.

The FOGMORE@FORGE project focuses on using DFOS measurements in a variety of roles with four main goals, (a) utilizing multiwell DAS recordings to provide accurate microseismic maps of fracture generation, (b) using reflected phases from microseismic events to image natural and induced fracture geometry, (c) using semi-permanent surface seismic sources (SOVs) and DAS to record timelapse VSPs for fracture compliance monitoring, and (d) using LF-DAS to assist in understanding the permeability of the connected fracture system. In this paper, we will attempt to provide a detailed description of the DFOS system deployed by the FOGMORE team at the Utah FORGE site, information on the installation and commissioning process, preliminary results for a range of fiber-optic data streams, and some lessons learned at this stage of the project, particularly relevant to fiber-optic cable design and monitoring infrastructure.

2. SYSTEM DESIGN & INSTRUMENTATION

In this section, we hope to provide a detailed overview of the DFOS cable design, secondary hardware, and sensing infrastructure used during our Utah FORGE experiments. We should note that this description is only relevant to the FOGMORE@FORGE cable; a flatpack including an alternative cable design was deployed by a UT/Shell team in the same well (e.g. Jurick et al. 2025).

Description of the DFOS Cable: Our goal in designing the sensing cable for the FOGMORE@Utah FORGE project was to provide reliable DFOS measurements (DAS, DTS, and DSS) at temperatures up to 265 C while simultaneously testing several new design elements. To improve DSS strain linearity we added a tight-buffered SM fiber dedicated for strain sensing. This decision was inspired by recent cross-sensor comparison studies for DSS linearity (Sasaki et al. 2021). To improve DAS recording sensitivity, we selected an enhanced back-scatter SM fiber (Silixa LLC, Constellation TM). We decided upon a bare ¼” OD tube-in-tube downhole cable design for deployment in 16B(78)-32. Broadly, this cable construction was inspired by designs used in the oil/gas, CCS, and geothermal industries and has a strong track record for deep reservoir downhole deployments. The cable was optimized for measurement and survivability at Utah FORGE with particular attention given to the temperature performance of different components. A nickel alloy (A825) was selected over SS316L for the outer tube (0.035” wall thickness, 0.25” OD) due to its improved corrosion performance across a wide operating temperature range and superior physical properties, particularly tensile strength. PFA belting was used for the tube interior and tight-buffered SMF fiber encapsulation; PFA provides the highest temperature rating currently available for a polymer fill material. The primary sensing fibers were housed in an inner FIMT (fiber-in-metal-tube) assembly constructed of SS-316L (0.2 mm wall thickness, 1.8 mm OD) and protected using a high-temperature hydrogen scavenging gel (LA4000). Within the FIMT were 5 fibers (2 x SMF, 2 x MMF, 1 x Constellation). Bend insensitive, hydrogen resistant glass chemistry was selected for all optical fibers as well as polyimide coatings to provide survivability to 300 C. The 2 multimode fibers (Verrillon VHM5000) were incorporated to enable double-ended DTS configuration to provide high measurement accuracy under adverse operating conditions. The 2 singlemode fibers (Verrillon VHS500) were included for secondary DAS and DSS measurements and as spare sensing components. The high backscattering fiber (Constellation, Silixa LLC) was included to provide an improved DAS noise floor with past studies suggesting a 20 dB improvement. The full cable was manufactured by Prysmian Downhole Technologies. Figure 2A shows a schematic diagram of the cable.

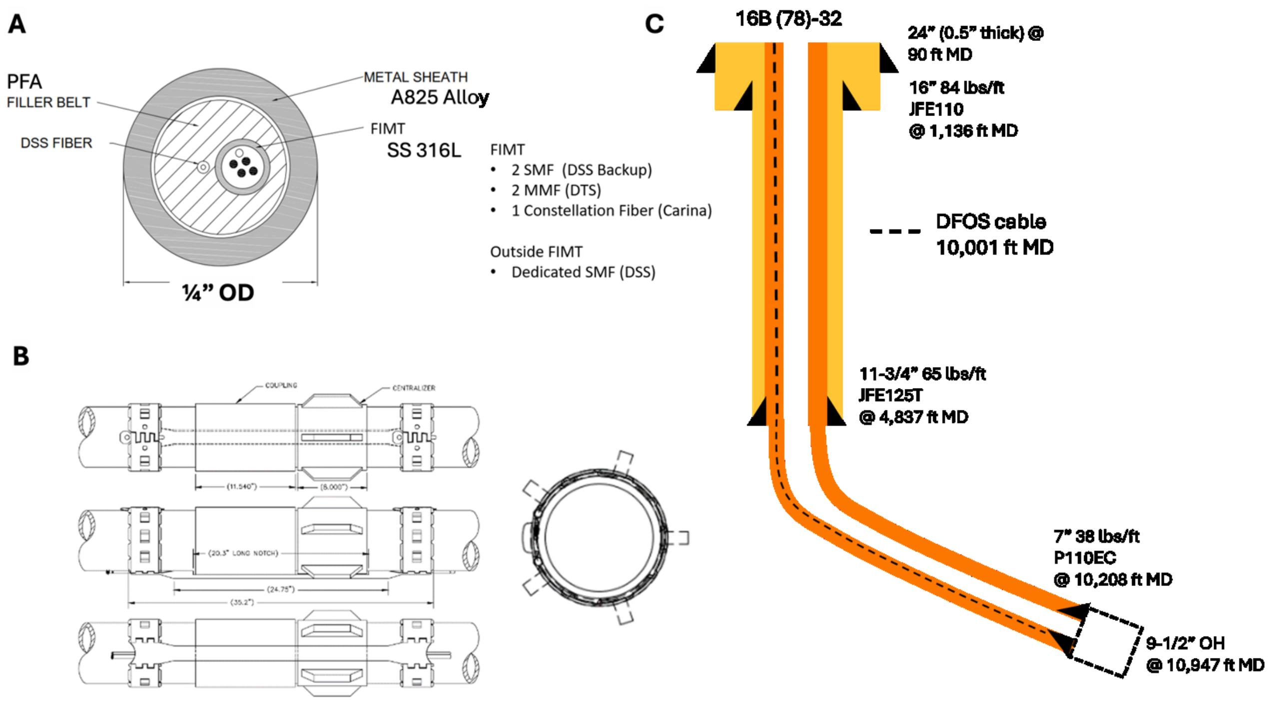

Figure 2: Design of the DFOS cable (panel A), solid body clamps (panel B), and well 16B(78)-32 (panel C).

The DFOS cable was received on May 24th, 2023. Unfortunately, a variety of manufacturing problems resulted in reduced performance, even before deployment at FORGE. While all fibers within the FIMT passed production OTDR tests at the factory (May 12th, 2023), we observed a gradual increase in optical loss during storage, after respooling, and at site drop-off. While this optical loss leveled off, the process left several fibers challenging to utilize for sensing. The tight-buffered SMF was not usable and likely broke during the PFA curing process. The increase loss levels generally decreased S/N levels for our measurements; our hypotheses concerning failure modes will be discussed later.

Secondary components: Beyond the DFOS cable, a variety of secondary components are required for downhole deployment including a bottom hole assembly, clamps, and a wellhead exit. Silixa's High Pressure Bottom Hole Assembly (BHA) was selected to provide cable end termination, functioning as both a seal and an enclosure to protect u-bend fiber splices enabling looped and double-ended measurement configurations. All seals were metal-metal and pressure testing was conducted prior to deployment. This assembly was manufactured in A825 alloy to match cable alloy performance at high temperature. The BHA was installed on a pup joint with an eccentralizer below the lower collar to protect the BHA during installation. Cross-coupling fiber optic cable clamp protectors (Fig. 2D) with solid body centralizers fixed the cable to the production casing. This also provided protection against abrasion with the borehole wall during deployment, in contrast to simple band clamp or mid-joint style designs. The use of solid body clamps was decided upon after past challenges with cable damage which occurred while running-in-hole in hard rock environments. Lastly, a custom-designed wellhead exit system was also developed, incorporating high-temperature-resistant components to withstand the extreme conditions associated with geothermal fluids. The 1/4" cable was routed through the wellhead, passed through an autoclave assembly and a compression fitting (Swagelok Co) to ensure proper pressure sealing.

DFOS Interrogator Suite, Processing, & Telemetry Infrastructure: The fiber optic cable was coupled to a state-of-the-art suite of interrogator units and two independent real-time analysis tool chains capable of processing DAS microseismic data on-the-fly. Rayleigh DAS data was acquired using a Silixa Carina interrogator unit, Brillouin DSS data was acquired using a Silixa iDSS unit, and DTS data was acquired using a Silixa XT-DTS system. Figure 3C and 3D show the recording system rack housed near the 16B wellhead in a customized instrumentation hut (Fig. 3A). A second DAS interrogator (Silixa iDAS v.2) was installed on the 78B pad in a small modular container (Fig. 3B) and connected to a previously installed vertical fiber in the 78B well extending to ~1202 m TVD. Both DAS interrogators acquired data with a fixed gauge length of 10 m throughout all acquisition periods. During later project stages, data was also made available for a third offset vertical well (Delano) by Fervo Energy. The use of multiple wells and interrogators allowed for decreased uncertainty during DAS microseismic operations. Figure 1B shows the relative locations of local wells at the FORGE site.

A key challenge for prompt DAS analysis is the management of the massive datastreams generated by large-N seismic acquisition. Particularly when recording at high sample rates (e.g. 10 kHz), DAS IUs can quickly generate data well in excess of telemetry capacity, on the order of TB to 10s of TB/day depending on acquisition details. To circumvent these challenges, we fielded two real-time DAS microseismic analysis tool chains, one commercial (Silixa LLC) and a second academic (Chamarczuk et al. 2023). Both systems processed the streaming DAS data on-site and generated "rough" automated hypocenter catalogs; analysis steps included preprocessing (filtering, decimation), event detection, and stack-based hypocenter determination. To facilitate dual analysis tool chains, all DAS data was written to a shared local RAID array connected to both systems via 10 GB optical switch, thus allowing near-realtime access.

Off-site telemetry was also required to allow data QC and export as well as sharing of data between the systems on the 16B and 78B pads which lacked a physical fiber interconnect. Primary offsite data transfer utilized a high-speed satellite connection (Starlink Services LLC) on the 16B container; the 3-6 MB/s uplink was sufficient to move post-processed DAS event data and catalog information but was not sufficient for raw data transfer. To move data between the two remote DAS IUs, a directional microwave link (RaCOM, Ray3) was used to connect the systems (dishes visible in Fig.3A/B) but exhibited insufficient bandwidth for continuous data streaming (~2 MB/s uplink), likely due to dish flexion and movement in the windy environment at FORGE.

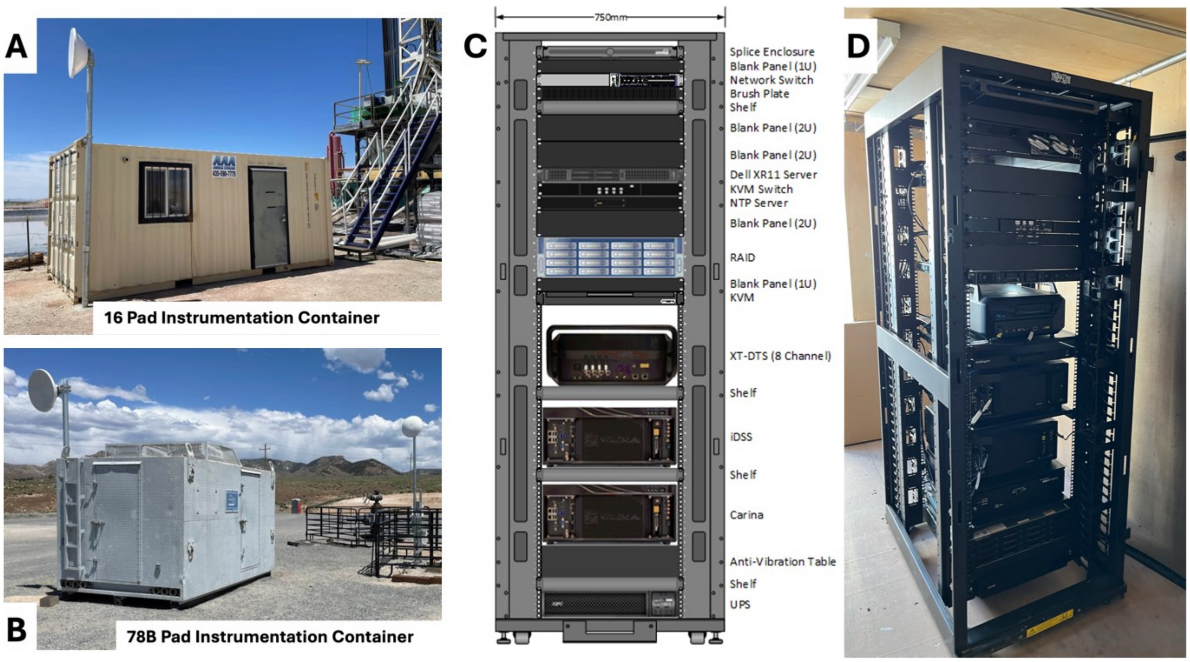

Figure 3: Instrumentation containers, telemetry systems, and the interrogator unit stack. Panels A and B show the instrumentation containers used to house the IUs located on the 16 (A) and 78B (B) pads. Panels C and D show the integrated DFOS interrogator systems in schematic and photo forms.

3. INSTALLATION & COMMISIONING

The system described in section 2 was designed and procured in 2022 and installed in June of 2023, immediately before the casing and completion of well 16B(78)-32. Fig. 2C provides the as-built well diagram. The FOGMORE DFOS cable was deployed on the 7" production casing string which extended to a depth of 10,208 ft MD (3111.4 m MD). A spooling unit and sheave was used to deploy the cable during the casing run as can be seen in Fig. 4A. The BHA was installed on a pup joint at a measured depth of 10,001 ft MD (3048.3 m MD). Integrity of the cable was tested at arrival, on rig-up, after every 10 casing joints, and upon reaching total depth. Solid body clamps (Fig. 4B) were utilized to protect the cable during the run-in-hole (RiH). Upon reaching total depth, a temporary termination was utilized to allow monitoring during cementation and flow-testing before running the permanent surface line run back to our instrumentation container. We should note that the DFOS cable terminated ~200 ft (~61 m) above the casing shoe with an additional 739 ft (225.2 m) of 9.5" open hole below leaving the lower 940 ft (286.5 m) of the well without sensing coverage.

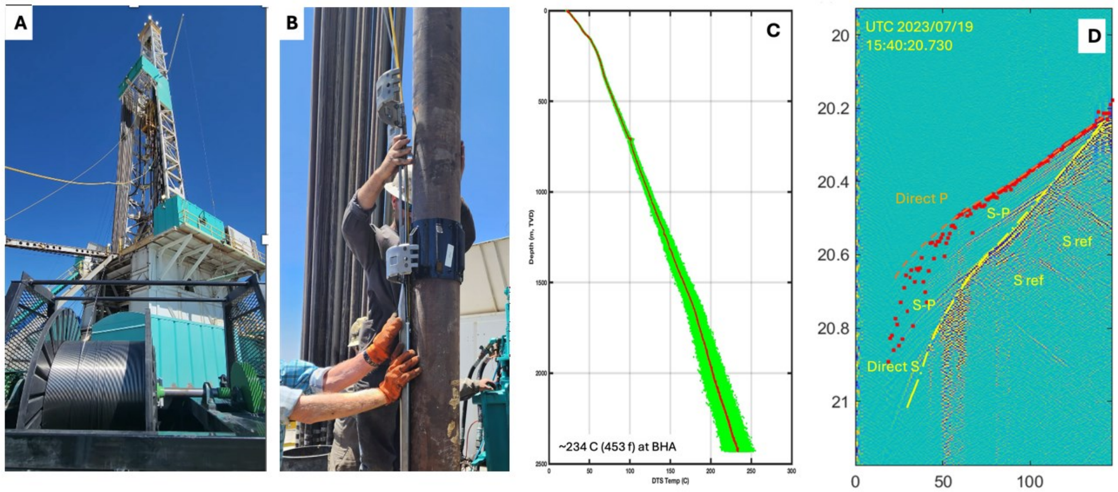

Figure 4: Installation and commissioning: Panel A shows the DFOS cable being run into well 16B. Panel B shows the cable being installed in a clamp assembly. Panel C shows an averaged DTS trace after equilibration suggesting a bottom-hole temperature at 10,000 ft MD of ~234 C. Panel D shows an example microseismic event which occurred during the 2023 circulation test.

Immediately after cementing, the integrated DFOS system was used to record microseismic events generated during early circulation tests. These tests occurred on July 19th and 20th (2023), mentioned in past studies (e.g. England et al. 2025, data in McClennan et al. 2024), and conducted to investigate flow pathways between 16A and 16B due to past stimulation activities in 16A. The injections were conducted at low flow rates to avoid generation of additional fractures. During these operations, the 16B DAS system described previously recorded at 10 kHz with 1 m channel spacing resulting in 3,264 channels; DAS recording occurred on the lowest loss fiber (MM). Data recorded in well 78B was sampled at a lower 1 kHz sample rate with the same spatial sampling. Despite the previously mentioned challenges with cable S/N levels, high quality microseismic data was acquired during these flow tests; figure 4D shows an example of an event near the toe of well 16B with select phases indicated in yellow. 257 events were detected and located using the real-time workflow and 3 dominant fracture planes were identified using DAS data from the two wells. Results from the 2023 circulation test were previously reported in Vera-Rodriguez et al. (2024, **A**) and a preliminary catalog is now available at the Geothermal Data Repository (Vera-Rodriguez at al. 2024, **B**).

Raman DTS and Brillouin DSS data were also acquired during the July tests and passively for extended periods in 2023. The DTS system functioned effectively on a single MM fiber; after warm-up of 16B, bottom-hole temperature was estimated to be ~234 C (see Fig. 4C). Unfortunately, the optical loss increases on the selected MM fiber resulted in slow degradation of the DTS data which was considered unusable later in 2023. DAS data was acquired passively for the fall of 2023 and the spring of 2024 in preparation for the April 2024 stimulation

4. PRELIMINARY RESULTS FROM THE APRIL 2024 STIMULATION

The described DFOS system was utilized during the stimulation and circulation experiments which occurred in April of 2024 (see England et al. 2025). After close to a year of operation in the EGS reservoir, the optical loss on the cable had slowly increased. Based on an evaluation of all fibers in March 2024, the decision was made to record DAS on the high back-scattering fiber (Constellation) which exhibited the best performance. In addition to passive recording on DAS, timelapse DAS VSP datasets were acquired during pauses between stages using semi-permanent surface orbital vibrators (SOVs). During the April stimulation, eight stages were pumped into injection well 16A and four stages were pumped into the production well 16B. The DFOS cable was further damaged during the 16B stages where the toe of the cable was lost during stimulation. Monitoring data was of reasonably good quality through the 16A stages with the exception of a short system failure. The entire lower section of the fiber, below the heel, was compromised due to fluid ingress during the long-term flow test in August of 2024. Despite these challenges, preliminary analysis shows a wealth of information captured during DFOS acquisition.

DAS Microseismic Event Detection and Location: As mentioned previously, dual detection workflows were applied to the borehole DAS microseismic data acquired by the DFOS monitoring system. This system was utilized for monitoring during the 16A & B stimulation sequence in April 2024. Event detection was conducted in real time using root-mean-square (RMS) waveform stacking on the continuous DAS microseismic data recorded during the 16A and 16B stimulations (April 3 2024 to April 22 2024), excluding approximately 13.5 hours of missing data (from April 6 2024, 00:18:22 to 13:42:15, UTC) caused by a FOGMORE system outage during the 16A injection from late stage 8 to early stage 9. The detection results were compared with the surface array catalog generated by the University of Utah Seismograph Stations (UUSS) (Niemz et al., 2024). Figure 5 shows a bar chart of detected microseismic events during the 16A stimulation from stage 3R to stage 10(6R), comparing the microseismic detectability of the FOGMORE downhole DAS system (gold) and the UUSS array (blue). Injection time of each stage are marked by red lines and each bin represents 30 mins. Unsurprisingly, the downhole DAS system demonstrated greater sensitivity to microseismic activity and detected significantly more events than the surface array, revealing clearer patterns and greater detail in how the event cloud evolved as injection progressed and stopped.

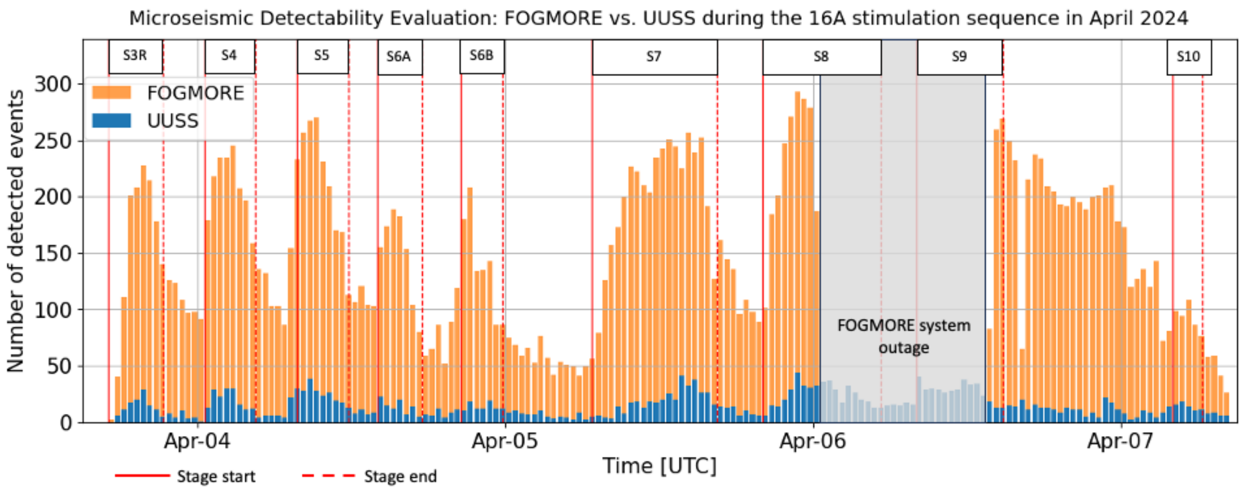

Figure 5: Microseismic detectability evaluation, event histogram: FOGMORE downhole DAS vs. UUSS during the 16A stimulation sequence in April 2024.

For hypocenter location analysis, a simplified 3D velocity was constrained using DAS observations from wells 16B, 78B and the Delano moitoring well (courtesy Fervo Energy). Calibration used a joint location and velocity model inversion with 45 microseismic events that had arrivals visible in the three wells. Using this model, all of the triggers detected during the April 2024 stimulation period were located. The hypocenter location results are shown in Figure 6. We used a relative location method where a set of reference events is selected to act as anchors for the relocation of the rest of the catalogue. The relative location process generates an empirical qualifier of the location result. This "Confidence Index" takes in attributes such as the SNR of seismic arrivals, correlation and distance to the reference event used for location among others. From a total of 23,839 triggers detected during the 16A stages, using a Confidence Index > 65 we can isolate 8,330 events with the most reliable location results. These are the events showed in **Error! Reference source not found.**. Upon inspection, we can observe that these events display arrivals in the three wells, which explain the reliability of their location result. Events with 45 < Confidence Index < 65 total to 6,914. These events show arrivals mostly only in well 16B or in more than one well but very weakly. Finally, the 8,595 events with Confidence Index < 45 are a mix of detections with very weak arrivals in 16B, false triggers, and failed locations. We should note that the microseismic cloud generated from our workflow, which utilizes only DAS data, is spatially quite similar to the results generated by groups using a combination of DAS and borehole geophones (e.g. England et al. 2025), showing several primary event corridors.

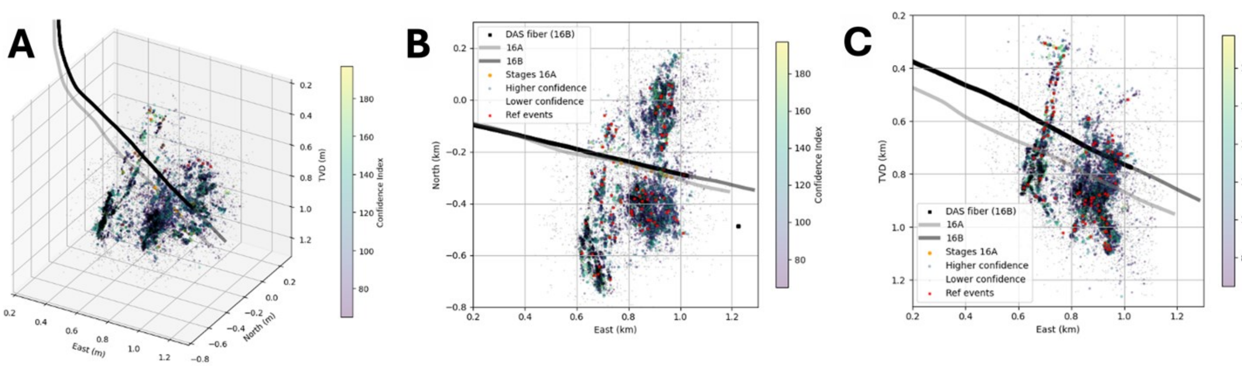

Figure 6: Three views of microseismic events detected using the 3 well DAS array during the April 2024 stimulation. Events for all stimulations shown.

DAS Microseismic Reflection Imaging: The abundant microseismic data recorded by the DAS arrays also provided an opportunity to use coherent phases beyond the first arrival for imaging, as recently demonstrated by Ma et al. (2024A) in the context of unconventional monitoring and Ma et al (2024B) during earlier Utah FORGE operations. Figure 7A shows an example of a microseismic event recorded on the DAS array close to the 16B; S scattered phases generated by stimulation are shown with dashed lines. We utilize the processing flow discussed in Ma et al. (2024A) including filtering, wavefield separation, and Kirchoff migration to localize the generated fractures in space and utilize the time series of events for timelapse imaging. Figure 7B shows an example of one migrated microseismic reflection image capturing the reflectivity changes generated by stage 8. The high reflectivity zone from stage 7 is still visible as a secondary reflector. Significantly, these reflections are probing the timelapse variability of fracture compliance, a property which informs aperture rather than the zones of fracturing/slip indicated by a microseismic event.

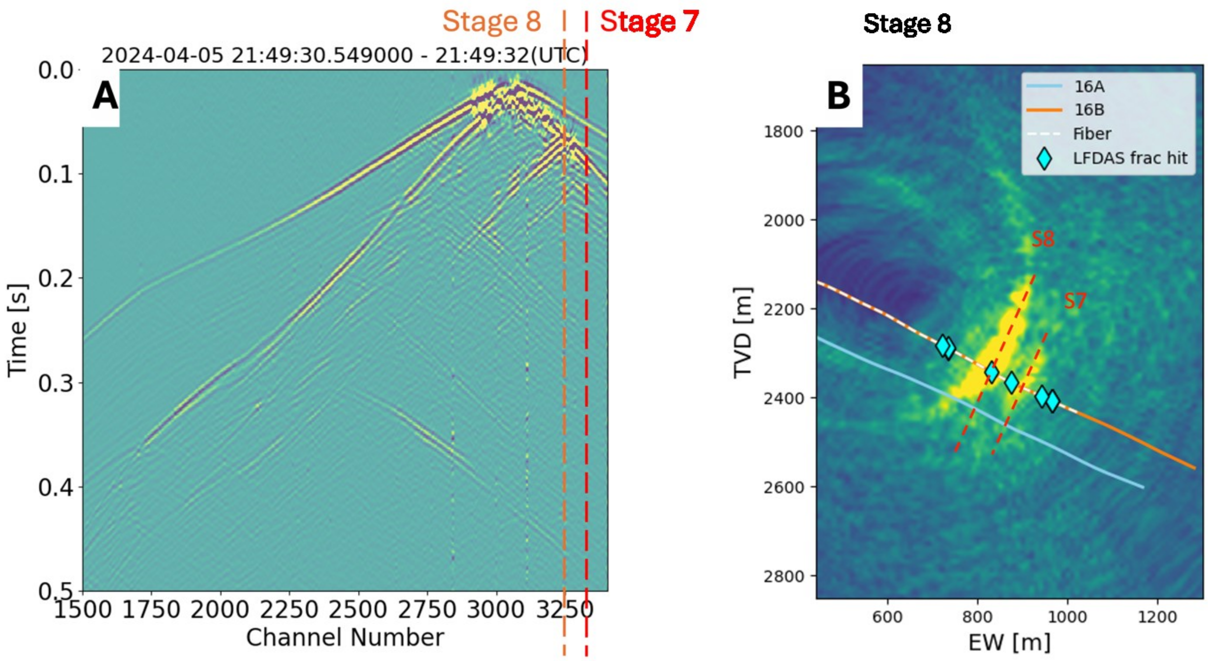

Figure 7: Example of microseismic reflected phases recorded by DAS (A) and the location of reflectivity change detected after migration (B).

LF-DAS: In addition to microseismic analysis, the DAS data was processed to extract low-frequency strain signatures which occurred during the 16A stimulation sequence. A slightly modified version of the workflow reported in Jin & Roy (2017) was utilized. Cable degradation resulted in more channel-to-channel noise but the primary fracture hits in 16B were visible, with the exception of the system downtime, as can be seen in Fig.8A. Using this dataset, a fracture hit map was created (Fig. 8B) which provides the mapping between stimulation zones, visible as thicker lines in Fig. 8B, and connectivity to well 16B as indicated by coded arrows. A key stage of interest is Stage 8 which was detected at considerably shallower measured depths and exhibited an asymmetric strain signature, suggesting a non-typical propagation pattern. We hypothesize that some interaction may be occurring between that hydraulic fracturing stage and a pre-existing natural fracture or fault system.

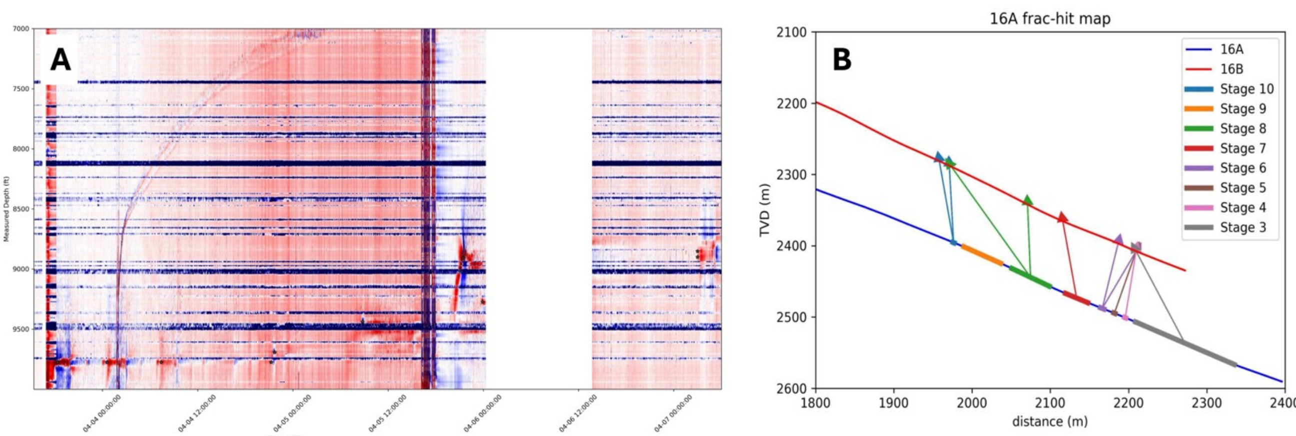

Figure 8: Processed LF-DAS results during the 16A stimulation sequence (A) and fracture hit map (B).

While these results should be considered preliminary, the experiment succeeded in demonstrating the broad utility of DFOS, and DAS in particular, for understanding zones of failure (DAS microseismic), changes in fracture compliance (DAS microseismic reflection imaging), and fracture connectivity (LF-DAS) in the context of EGS. At present, these components are being refined and merged together to create an improve fracture network and assist in constraining high-resolution reservoir models. The timelapse SOV/DAS dataset mentioned previously is also undergoing processing; while this analysis was complicated by reduced S/N related to the cable, hints exist of the same fracture reflectivity changes seen in microseismic reflection imagery at depth. Recent studies have suggested that the time-resolved reflectivity obtained from such DAS/VSP datasets can be utilized to track pore pressure variation and the coupled interaction between induced and natural fracture sets (e.g. Correa et al. 2024, Glubokovskikh et al. 2024).

5. DISCUSSION & LESSONS LEARNED

Despite the high-quality data sets ultimately obtained, a variety of lessons were clearly learned in terms of data utility, cable design, testing protocol, and acquisition strategies. While our effort is not yet complete, we feel comfortable providing a brief overview of some challenges we encountered.

- **DFOS Value**: The first, and perhaps the most positive, lesson learned was the high value of DFOS data in EGS monitoring. DAS was highly effective in microseismic event detection and location at scale, particularly when multiple wells could be incorporated. For the April 2024 experiment, the use of a local well (16B) as well as multiple offset wells (78B and Delano) allowed generation of both a large catalog and accurate location of events during stimulation. The availability of DAS microseismic reflection imagery and LF information is significantly improving our understanding of fracture geometry, dynamics, and connectivity; no other sensor suite can replace this combination of microseismic, seismic imaging, and geodetic information. Despite challenges in cable manufacturing, the system survived for a year at EGS conditions before mechanical damage during hydraulic fracturing led to fluid ingress.

- **DFOS Cable Testing**: An obvious lesson learned was the need for extensive pre-deployment cable testing. In our case, a very tight procurement timeline was required to align with the drilling and casing schedule, precluding multiple iterations of cable evaluation. DFOS cable production often has significant lead times (4 months+) and in our case the lead was over 7 months between design and delivery. While the design we selected was close to prior successful production runs, the incorporation of the PFA belting, a tight buffered fiber element, and a slightly larger FIMT with more fibers was a new step. Future experiments might consider a longer design/prototyping period (1.5 - 2 years+) if multiple testing iterations are required.

- **DFOS Cable Construction Lessons**: As mentioned previously, an unfortunate observation was the increase in loss as a function of time in the deployed cable. This effect was first observed immediately after delivery where, as mentioned previously, optical losses appeared to increase over time even before downhole deployment of the cable. Our current hypothesis was that this was related to manufacturing/curing problems in the PFA buffer which resulted in a gradual increase in microbend losses. This effect was likely exacerbated by the tight packing of elements in the cable and a low excess fiber length (EFL) in the cable. We would recommend careful attention to EFL and perhaps more conservative component spacing in future designs.

- **DFOS State-of-Health Monitoring:** One challenge we experienced was changes in fiber optical loss over time which necessitated modified acquisition plans (e.g. switching monitoring fibers). Future deployments might consider approaches for real-time system state-of-health (SoH) monitoring using either an automatically switched OTDR to monitor individual fiber loss or extraction of SoH information from distributed sensing data streams. Particularly when fiber-optic systems are a key part of site monitoring infrastructure (e.g. traffic-light system or reservoir management) a SoH system generating useful fiber health indicators could aid decision making.

- **DAS Data Transfer/Management:** Lastly, a challenge at our site like many DAS deployments was the data volume generated during acquisition. While our two real-time systems provided limited products during operations, over 0.3 PB of data has been generated to date. This volume exceeds any reasonable satellite telemetry uplink capacity and has required sequential RAID system copies and manual transportation. This has presented a particular problem for reprocessing efforts, archiving, and external data distribution. Insufficient project funds were allocated for the archiving task in particular; future efforts might consider a substantial early investment in off-site storage/distribution infrastructure, perhaps coupled to DOE computing capabilities (e.g. NERSC), to maximize the capacity of research teams to utilize generated datasets. Likewise, solutions to provide high bandwidth "last mile" telemetry between EGS sites and commercial telecom facilities would be valuable.

6. CONCLUSION

In support of the Utah FORGE project, the FOGMORE team designed (2022), deployed (2023), and utilized (2024) an advanced DFOS monitoring system for EGS system characterization, including an integrated downhole cable rated to 265 C, an advanced suite of fiber-optic interrogators (DAS/DSS/DTS), and a real-time processing infrastructure to allow rapid data analysis and reduction. Despite cable manufacturing challenges, a trove of valuable data was generated including an excellent microseismic catalog from the April 2024 stimulation, unique microseismic reflection datasets, and strain datasets constraining fracture hits to well 16A. Future efforts will focus on utilizing this unique time-resolved dataset to better understand the fracture network at FORGE and providing constraints for the advanced THM models now being developed for the site.

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