

Seismic Monitoring for the Multi-Month Circulation at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE)

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ABSTRACT

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a U. S. Department of Energy funded, field-scale laboratory dedicated to developing and testing technologies for the commercialization of Enhanced Geothermal Systems (EGS). Past operational hydraulic fracturing activities at Utah FORGE have included stimulations in 2019, 2022, and 2024 and a month-long circulation test in 2024. Each of these activities has been seismically monitored. Seismic monitoring is focused on both implementation of the Traffic Light System and imaging microseismic fractures in the reservoir. Seismic monitoring has evolved from operation to operation with the advent of new tools and advances in seismic processing. For the planned 2026 three-plus month-long circulation test, we propose to integrate data from deep borehole DAS, geophones in three deep boreholes, and data from geophones in three shallow (~300 m) boreholes to generate a real-time catalog. Separately, we will integrate data from the surface and shallow posthole and borehole stations into a machine-learning based algorithm to build an independent catalog. This catalog together with regional seismic monitoring efforts will be used to implement the Utah FORGE Traffic Light System and together with the hydraulic pumping data will be used to test an Adaptive Traffic Light System. We will also deploy a temporary geophone network. The geophone network will build on past temporary geophone experiments and deploy a mix of patches and single element geophones to enhance post-processing efforts.

1. INTRODUCTION

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a Department of Energy (DOE) field scale laboratory for testing new technologies and promoting research to help develop a commercially viable path to enhanced geothermal systems (Moore et al. 2020). Seismic monitoring is a key aspect of Utah FORGE. The potential for induced earthquakes provides both a societal acceptance issue if events are large or become a nuisance (e.g. Majer et al., 2016; Schultz et al., 2020) and a mechanism for better understanding the geothermal reservoir (e.g. Dyer et al. 2023; Niemz et al., 2024, Niemz et al., 2025). For each operation at Utah FORGE the seismic team develops a seismic monitoring plan that is reviewed by the Utah FORGE Science Technology Advisory Team and the DOE. With each operation we assess what was learned during past operations and what the goals of the current operation are. As a result, seismic monitoring at Utah FORGE has evolved with each operational activity. Pankow et al. (2025) describes the evolution of seismic monitoring of operational activities for past operations and lessons learned. In addition to seismic monitoring during operational activities, Utah FORGE has a local network where real-time data is integrated into regional operations at the University of Utah Seismograph Stations (UUSS) (Pankow et al., 2019). Data from these stations are archived in near-real-time at the EarthScope Data Management Center. As a member of the U. S. Geological Survey (USGS) Advanced National Seismic System, seismic events ($M > 1$) and associated products like ShakeMaps in the Utah FORGE area are archived in the USGS Comcat catalog.

In this paper, we describe the seismic monitoring plan for the upcoming multi-month circulation, which will occur later this spring. For a formal seismic monitoring plan to be developed the objectives of the monitoring need to be stipulated. These objectives may include things such as detection and location of microseismicity, time-lapse monitoring, or calibrating the flow. Each of these objectives has different seismic monitoring requirements. For the multi-month circulation, the objectives are to produce a high-precision catalog in near-real-time, monitor for alert thresholds in the revised Utah FORGE Traffic Light System (TLS). We also plan to test an Adaptive Traffic Light System (ATLS) and to deploy a temporary geophone array to collect data for source process analysis and to refine seismic velocity models.

2. SEISMIC NETWORK

A key aspect in seismic monitoring during the multi-month circulation is distinguishing seismic events originating in the Utah FORGE reservoir and those originating in the Cape Project reservoir of Fervo Energy Inc.. As in past operations Utah FORGE will produce two microseismic catalogs. One catalog utilizes the downhole instrumentation and a second that utilizes the surface and near-surface seismic network. Both catalogs will be generated in near-real-time.

2.1 Borehole Seismic Network

Geo Energie Suisse (GES) will lead monitoring of the borehole seismic network. The seismic network will utilize DAS in coil-tubing located in 16B-32, a single-level Avalon PSS tool in the 56-32, 58-32, and 78B-32 wellbores set at a maximum temperature of 150°C (Figure 1). New to this operation, GES will also integrate the data from the shallow wellbores (300 m) FORK, FORK2, and FORK3. This data will flow into the GES instance of the Divine software (Dyer, 2011) for processing. The addition of the shallow wellbore data will improve the azimuthal coverage but will entail the application of a two-layer velocity model of the sediments and granite for co-locating using the PSS sensors in the granite with the FORK sensors in the sediments for the first time at FORGE. The hodogram performance of the PSS tools will also be assessed in case it is necessary to locate with a smaller network in future. This network has the potential for microseismic detection to M -2.

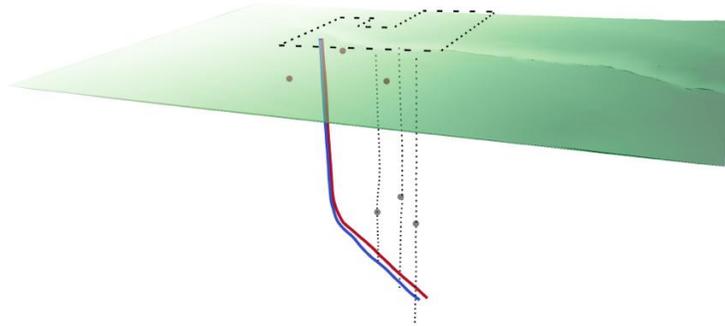


Figure 1: Borehole seismic network. Vertical dashed lines are wells 56-32, 58-32, and 78B-32 each equipped with a single-level Avalon PSS tool. Red line is well 16B-32 equipped with DAS in coil tubing. Red dots near to surface are shallow wellbores FORK, FORK2, and FORK3 equipped with geophones. Dashed line on surface is the Utah FORGE footprint.

2.2 Surface and Near-Surface Seismic Network

UUSS will lead monitoring of the surface and near-surface network. This network consists of geophone data from three shallow (300 m) wellbores (FORK, FORK2, and FORK3), broadband and for close station accelerometer data from six postholes (30 – 40 m), six broadband stations located on bedrock (FOR#), one short-period geophone (NMU), and three accelerometers (FORB, FORW, MHS2) (Figure 2; for more details see Pankow et al., 2025). All data flows to UUSS where it feeds two separate operating systems and from where it is archived at the EarthScope Data Management Center. For monitoring TLS alarm thresholds, triggering algorithms at UUSS have been refined to detect events $M > 1$. These events are reviewed by UUSS analysts and are archived at the USGS Comcat. For events $M > 2.5$, ShakeMaps (Wald et al., 2005) are automatically generated and are also posted to Comcat. ShakeMaps are maps of ground motion and intensity. Utah FORGE has not generated an event at this threshold. However, there was a recent event at the Cape Project that resulted in a ShakeMap (Figure 3). Note for these small magnitude events the resulting ground motions are low. For this event there were no felt reports.

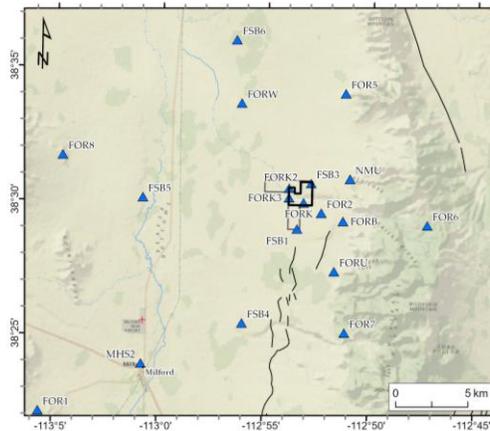


Figure 2: Utah FORGE local seismic network. Blue labeled triangles, locations of seismic stations. Black outline current Utah FORGE footprint. Gray outline, original Utah FORGE footprint for reference.

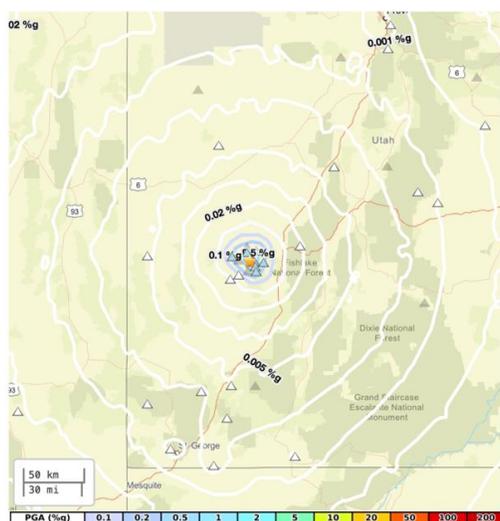


Figure 3: Peak ground acceleration map determined with ShakeMap for the 9 December 2025 M 2.7 earthquake located in the Cape Reservoir.

For monitoring fractures within the reservoir, the data from a subset of the surface and near-surface stations and data from one of the three deep wellbores will be integrated into a machine learning and migration algorithm, *qseek* (Isken et al., 2025; Niemz et al., 2024) to generate an automatic microseismic catalog. Events in this catalog are not routinely reviewed. However, experience (Niemz et al. 2024; Niemz et al., 2025) indicates that events $M > -1$ are real events and events $M > -0.5$ have a reasonable automatic location. Importantly, the automatic locations determined in *qseek* are sufficient for distinguishing events between the Utah FORGE and Cape reservoirs (Figure 4). This automatic catalog is also used to alert when 10 or more $M > 1$ events occur within 24 hours and to see if seismicity is migrating away from the reservoir.

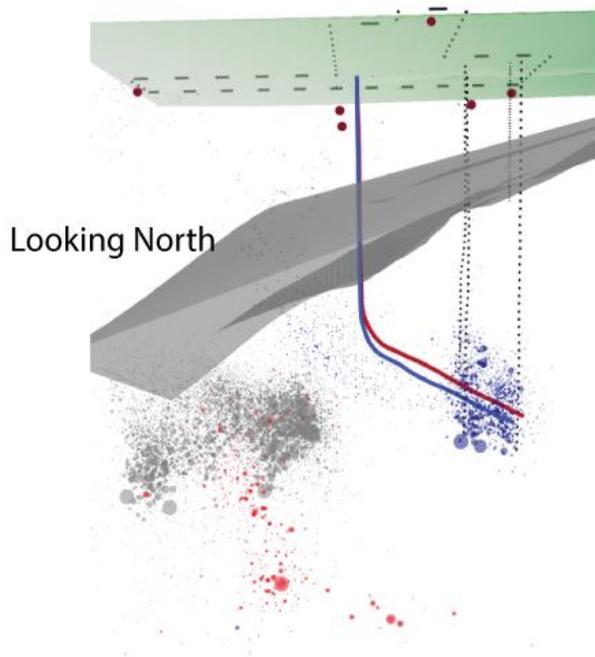


Figure 4: Microseismicity from Utah FORGE operations (blue circles) and Cape (gray and red circles). The green box represents the surface and the gray polygon, the top of basement. Even though the two reservoirs are separated by less than a kilometer in places, *qseek* automatic locations provide sufficient resolution to distinguish between the reservoirs.

2.3 Geophone Array

In addition to the more established seismic monitoring networks, we also plan a nodal geophone deployment (Figure 5). The goal for this temporary deployment is twofold. The first target is to re-instrument some of the dense patches from Niemez et al. (2025). This data will be used for seismic source studies. The second target is deployment of a dense array with a random geometry (Mordret and Grushin, 2025). This array will be used for microseismic event location and for subsurface seismic imaging. The geometry is chosen to reduce aliasing when using ambient noise or local earthquake tomography for retrieving seismic velocity models.

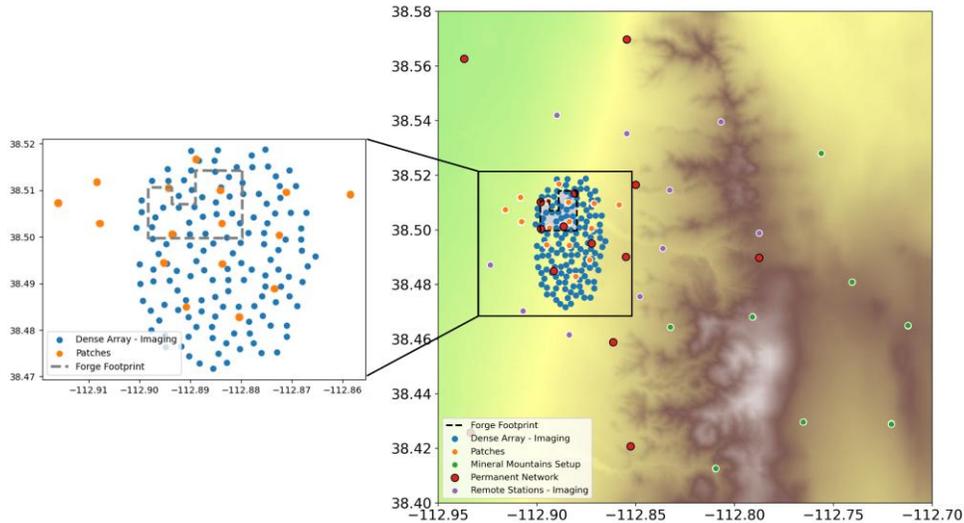


Figure 5: Surface seismic monitoring design for the upcoming circulation in 2026. Red: Permanent stations, Blue: Dense temporary array for imaging purposes, Orange: Nodal patches for improved moment tensor analysis, Purple: Remote nodes to improve locations, Green: Remote nodes in the Mineral Mountains.

3. TRAFFIC LIGHT SYSTEMS

Traffic Light Systems (TLS) have been developed to help provide metrics for adjusting operational activities in energy related fields (e.g. Bommer et al. 2006; Grigolli et al., 2017). Traditional TLS are reactionary. If a magnitude, ground motion, or felt intensity is exceeded, then there is a change in operations, and for cases when the red threshold is exceeded, operations halt. In contrast, Adaptive Traffic Light Systems (ATLS) integrate information such as hydraulic pressures and volumes and models of how seismic sequences develop to provide forecasts that can be used to modify operational activities before an alarm threshold is reached (e.g. Grigolli et al., 2017; Baisch et al., 2019; Király-Proag et al., 2017; Mignan et al., 2017). At Utah FORGE we utilize a traditional TLS for operations and are testing ATLS for situational awareness and to improve the models and advance knowledge necessary for improved ATLS.

3.1 Traditional Traffic Light System

As with the seismic monitoring, the Utah FORGE TLS (Pankow et al. 2020; Pankow et al., 2025) has evolved as more has been learned about response of the reservoir to fluid injection and to account for the differing operations between Utah FORGE and Cape. In a simple sense, Utah FORGE reaches an amber threshold for $M > 2$ events and red for $M > 3$ events (Table 1). For amber events, the response is a controlled flowback and a pause in operations until a revised operational plan can be devised. For red, there is also a controlled flowback, however, operations cease. The first modification to the TLS was in response to the Cape project. We now distinguish the location of the event by reservoir. For events in the Utah FORGE reservoir, we proceed as in the original TLS. However, for amber alerts generated within the Cape reservoir, Utah FORGE will continue operations. Red alerts in either reservoir will require a controlled shut down of activities. This is to account for and address potential societal issues.

Table 1: Overview of the traffic light system in place at the Utah FORGE site for the multi-months circulation test in 2026 (adapted from Pankow et al., 2025)

	Green	Yellow	Amber	Red
Magnitude threshold	$M < 2.0$	10 events with $M \geq 1.0$ in 24h	$2.0 \leq M < 3.0$	$M \geq 3.0$
Location criterion for magnitude-based TLS activation		Events in the Utah FORGE reservoir	Event(s) in the Utah FORGE reservoir	Event in the Utah FORGE reservoir or in the Cape project reservoir
Geometrical criterion			Rapid migration (500m in 24h)	
Efficiency criterion			Decline in efficiency (5% in 24h)	
Action	Continue with program as designed	Modification of the operational program	Stop injection, controlled flowback until revised operational plan	Controlled shut-in and securing of the well

The more recent adjustment to the TLS is in response to the 3 km fracture growth observed during and immediately after the 2024 circulation (Figure 6). This adjustment makes additions to the previous TLS thresholds; nothing is removed. The key provision in the revised TLS is that we will not shut-in following the circulation. We also formally introduce a Yellow threshold. Yellow will take into account seismic observations that result in modifications to operations versus pausing or ceasing operations. For Utah FORGE, 10 $M \geq 1$ in 24 hours and events propagating along a potential planar structure will be treated as adaptive features within this TLS, and as with ATLS, operations may be modified to change the seismic response. In addition to the Yellow threshold, we add two additional levels to the Amber threshold, which results in a pause and potential change to operations: (1) a rapid migration (500m in 24 hours) of reviewed and relocated seismic events and (2) a decline in efficiency (5% in 24 hours) during circulation (Table 1). The revised plan will soon be available at the geothermal data repository.

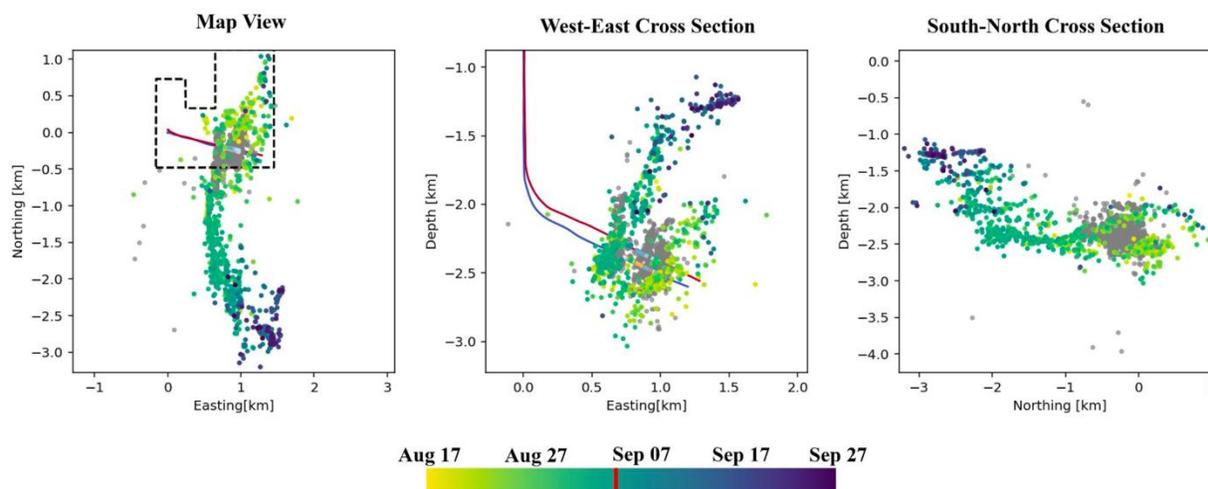


Figure 5: 2024 Utah FORGE circulation microseismic catalog (colored by time). Gray circles 2024 stimulation catalog (Niemz et al., 2025). Dashed polygon shows the Utah FORGE footprint and blue and red lines the Utah FORGE injection and production wells, respectively. The red bar in the time color bar scale denotes the time of shut-in.

3.2 Adaptive Traffic Light System

Adaptive Traffic Light Systems are designed to work in parallel to classical set-thresholds TLS, and allow for data-driven, forward-looking and probabilistic decision-making support for operators of a project. An ATLS framework has been tested at Utah FORGE for the 2022 and 2024 stimulations using three families of forecasting models: An empirical model linking injected volume to the seismicity rate (EM1; Mignan et al., 2017); a machine learning model taking in available time series to derive seismicity rate (ML1; Mignan et al., 2024); and a physics-informed model linking 1D flow to seismicity rate (HM1D-CAPS; Clasen Repollés et al., 2025). Orchestration of the forecasts and models is done using the rt-Hermes open-source software, which allows both for replays and near-real-time operations (Schmid et al., 2025; Ritz et al., 2025).

For the 2022 stimulation, seismic data were replayed through the ATLS workflow to produce forecasts that were then compared to the data (Lanza et al., 2026). The results show the promise of the models that have been developed for Utah FORGE. In 2024, ATLS was tested in real-time using the first two families of model, and in replay mode using all three families to evaluate the performance of the models (Ritz et al., 2025). Real-time operations highlighted the challenge of integrating non-standard data formats on the fly, including delays due to data gaps or processing time of the seismic catalogs leading to loss of synchronicity between hydraulic and seismic data streams. However, the produced forecasts were again informative, although not used at the time for on-site decision-making. Figure 6 shows an example of the fitted and forecasted rate of seismicity for stage 9 of the 2024 stimulation at Utah FORGE.

For the multi-month circulation, we use the *qseek* catalog together with the hydraulic data to generate ATLS forecasts. This is the first time we are aware that ATLS will be applied to a long-duration circulation (ATLS having been tested against injection operations mostly). Two families of models (EM1 and ML1) have been tested against the 2024 circulation data, using both injection rate and net volume (i.e. injection minus production) as a proxy for the flowrate. For circulation operations, the use of the net volume is showing promises as a better predictor of seismic behavior (Brodsky & Lajoie, 2013), however, we are expecting to assess and modify the nature of data flowing to the models throughout operations.

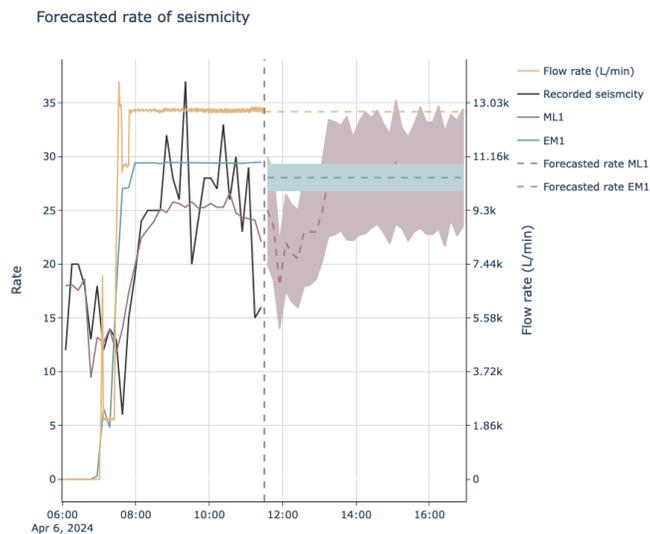


Figure 6: Forecast of the seismicity rate in near-real-time during stage 9 of the 2024 stimulation at Utah FORGE after 4.5h of injection. The forecasting horizon (UTC11:30) is marked by the vertical dashed line. The yellow line shows the injection rate with the dashed line right of the forecasting horizon showing the planned injection rate used by the models for the forecast. The black line shows the recorded seismicity rate. Blue and pink tones show the fitted seismicity rate (solid line), forecasted rate (dashed) and 1σ confidence interval (shaded area) for model EM1 and ML1 respectively.

4. CONCLUSIONS

Utah FORGE will be conducting a multi-month circulation beginning spring 2026. These operations pose new challenges for seismic monitoring at Utah FORGE given the duration of the circulation and the potential for simultaneous activities in the Cape Project. Like past operational activities, Utah FORGE has assessed the objectives for seismic monitoring and lessons learned from past activities to develop a seismic monitoring plan for this operation. The TLS was also reviewed and updated based on past operations. New aspects of the seismic monitoring include: (1) the shallow (300m) wellbore data will be integrated with the deep wellbore geophone and DAS data; (2) data from one deep wellbore will be integrated with stations from the near-surface and surface network into *qseek*; (3) we will redeploy some geophone patches, but the bulk of the geophone deployment will test a random array geometry; and (4) we will integrate ATLS with the operational catalog determined with *qseek* to develop seismicity forecasts.

5. ACKNOWLEDGEMENTS

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