Utah FORGE 2022 Seismic Workshop Report

DECEMBER 19, 2022

DE-EE0007080

UNIVERSITY OF UTAH

UTAH FORGE
U.S. Department of Energy

UTAH FORGE 2022 SEISMIC WORKSHOP REPORT

Enhanced Geothermal System Testing and Development at the Milford, Utah FORGE Site

Utah FORGE
University of Utah
423 Wakara Way, ste 300
Salt Lake City, UT, 84108

Prepared for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Contract DE-EE0007080

Author: Kristine Pankow

December 19, 2022

UTAH FORGE 2022 SEISMIC WORKSHOP REPORT

Utah FORGE held a two-day workshop on the University of Utah campus in Salt Lake City, Utah on September 26 and 27, 2022 to share what was learned from the seismic monitoring during the 2022 stimulation. This was an invitation only event for those that had actively collected data and/or performed a seismic related experiment during the stimulation, seismic experts from the Utah FORGE Science Technical Advisory Team, and the Utah FORGE Project Management Team. Table 1 lists the participants and affiliations. The format of the meeting was structured to be in-person to facilitate discussion. There was a Zoom link for the presentations for colleagues of those attending the meeting and two of the presentations were given virtually. The meeting was structured to cover four key topics: (1) seismic instrumentation, (2) seismic network design, (3) seismic monitoring protocol, and (4) development and implementation of seismic traffic light systems. Talks were grouped into four subcategories: (1) Introduction and overview, (2) Borehole geophone monitoring and instrumentation, (3) Surface seismic monitoring, and (4) Downstream monitoring products. The meeting was concluded with a discussion on what future geothermal seismic monitoring should look like for both Utah FORGE and enhanced geothermal systems more generally.

Presentation Summary

Introduction and Overview

The goal of the first set of talks was to make sure all participants were familiar with the motivations for and operational activities for the 2022 stimulation at Utah FORGE and details of the operational seismic monitoring. The meeting began with a welcome from Utah FORGE P.I. Joe Moore. Moore described the activities of Utah FORGE to date and provided an overview of future plans. In the following presentation John McLennan went into the details of the 2022 stimulation. One of the main goals of the stimulation was to learn where the fractures grew in order to help locate where the second deep deviated well will be drilled. There are and were many technical challenges in both drilling and stimulation. Primary challenges are related to the high temperatures and unknowns about in-situ reservoir characteristics. In the 2022 stimulation, bridge plugs were used to establish three separate zones for stimulation. The three stimulations each had different characteristics. Before initiating Stage 1 activities, a check shot was fired in the open hole section of the borehole to orient the seismic sensors and to calibrate the velocity model. Stage 1 stimulated the open hole section at the toe of the well using slickwater. Stage 2 perforated the casing in the well at 10,560’ to 10,580’ MD and pumped slickwater. During Stage 2, there was a planned pressure drop to test the seismic response. Stage 3 perforated the casing at 10,120’ to 10,140’ MD and pumped using a microproppant. The pressure data suggest a classic penny shaped fracture growth consistent with radial fracture growth. John identified a number of questions/considerations that the seismic data could provide information on:

1) Fracture complexity – role of natural fractures?
2) Hydraulic shearing as a component of effective stimulation?
3) Establish degree of connectivity (desirability of intersection)?

4) Thermal depletion and conformance
5) Methods of monitoring fracture growth – improving resolution
6) Inferring when fracture growth becomes problematic – risk analysis, mitigation protocols, stakeholder involvement, traffic light systems?

The next two talks in this section shifted to seismic aspects of the stimulation. In the first of these talks, Jim Rutledge presented the plan and the reality for seismic monitoring of the stimulation. Based on modeling work that had been performed by Ben Dyer (GES), the plan was to have an 8-level geochain string at reservoir depth (final depth constrained by the temperature specifications of the tools) in each of the three deep monitoring boreholes, 56-32, 58-32, and 78B-32. In addition, the DAS cables in 78-32 and 78B-32 would be monitored by Silixa and GES would test a three level fiber optic string (Avalon BOSS tools) in 78-32. Data from all the geochain tools would be integrated and processed by GES in near-real-time. The geophones were spec'd for temperatures < 210°C and the Camesa wireline cable for temperatures < 246°C. In a second stage of monitoring, 2-level Avalon passive seismic sensors (PSS) would be placed at reservoir depths following the stimulation. These tools had a temperature rating < 260°C. In practice, it was learned that the geochains had a temperature limit of ~180°C. This lesson was learned progressively while in the field. The instrumentation not meeting the specifications led to a modified monitoring plan. For all stages there was data from the DAS cables and the BOSS tools. For stage one, there was a single geochain string in 58-32 (max depth 6700'); stage two, the string in 58-32 and a two-level PSS string in 56-32 (max depth 8315'); and stage three, the string in 58-32, the PSS tools in 56-32, and a geochain in 78B-32 (max depth 6200'). While the PSS tools were operational in 56-32 for stage two and three, those tools failed within days of the end of the stimulation as did the other PSS strings that had been deployed in 58-32 and 78B-32. In all cases, the temperatures of deployment were well below the temperature specifications for the tools and cable. The PSS tools were returned to Avalon who provided a fix to the sensor and redesigned the cablehead. At the end of the meeting Jim was returning to Utah FORGE to redeploy the tools using a new cable (Schlumberger 7-46A-XXS wireline). In summary:

1) The digital geochains active cooling worked poorly limiting the depth access
2) PSS analog systems appear to have failed mostly in cableheads, but long-term specifications have yet to be proven
3) The high-temperature Camesa cable performed extremely poorly
4) DAS behind casing failed mechanically during installation limiting the depth extent, but the long-term performance looks good. However, the sensitivity is still poor compared to geophone performance
5) The BOSS fiber-optic receiver string is still somewhat of an unknown

In the final talk of this section, Dimitrios Karvounis (GES), described the process in creating the seismic reference catalog. A team from GES supervised and processed the seismic data, while on-site at Utah FORGE for the stimulation. Over 10,000 micro-events were detected in the field during the stimulation. A subset of these events was located in near-real-time. This initial processing showed that the seismicity occurring in all stages grew upwards and was elongated in the north-south direction. In the months following the stimulation the catalog was refined and a reference catalog of 211 (stage 1), 957 (stage 2), and 1431 (stage 3) events were released to the Geothermal Data Repository. Dimitrios explained the details of the processing that was used to build the reference catalog. These steps included calibrating the velocity model using the checkshots, merging the available data, applying a bootstrap technique for triggering and a separate bootstrap technique to data from 58-32 for auto-location, and then visually inspecting all auto-located events and adding manual P- and S-picks from available tools including the BOSS. In a separate effort, GES is creating a catalog of events that can be detected and a magnitude determined. This larger catalog needs more quality control but will eventually allow more robust statistical analysis. This catalog contains > 3,000 events with magnitudes stage 1, > 5,000 for stage 2, and > 15,000 for stage 3. In an additional effort, there is work to assess location resolution using relative relocation. Using this analysis, it was found that the relative error for stage 3 was 8' and for stage 1 23'. Based on this analysis, GES conclude that structural interpretations may reasonably be based on the Stage 3 locations, but stage 1 & 2 distributions should be treated with caution.

Borehole Geophones

In the next two talks, we learned more about the downhole monitoring. In the first talk Alejandro Martinez, Schlumberger (SLB), described SLB's contribution to the 2022 monitoring. In addition to seismic monitoring tool conveyance, SLB provided initial fracture network characterization through borehole imaging and 3D far field sonic, and ran the vibroseis acquisition for the post-stimulation VSP. SLB provided downhole tool conveyance (with 3rd party cable and geophones) for boreholes 58-32 and 56-32. Using the checkshots, they oriented the tools in 58-32 and 78B-32 and were able to calibrate the velocity model with a dipping granite interface. They did not integrate the data from the geophones in 56-32 into the processing, because they were unable to orient the tools during an event. The field seismic processing was delayed a few hours behind real-time due to an issue with file formatting updates and compatibility. Using the calibrated velocity model and the geochains in 58-32 and 78B-32, they built an earthquake catalog for Stages 1, 2, and 3. The detections included events down to Mw -4. The locations were quite different to those in the GES catalog; there was much larger scatter and no clear indication of upward fracture growth. SLB also attempted moment tensors for four events from stage 3. These were double-couple events and showed a tendency for strike-slip mechanisms.

In the next talk, Ben Dyer (GES), provided a recap of some of the lessons that were learned from the planning through operations of the seismic monitoring of the 2022 stimulation. The key points that Ben covered included: (1) Complexity of the Monitoring Network, including sensors and time synchronisation; (2) Velocity Calibration and Sensor Orientation; and (3) Field Preparations and Operations, including real-time processing. Regarding complexity of the network, as described in Jim Rutledge's talk, there were multiple boreholes and both traditional and fibre optic sensors. Ben elaborated on this to point out that the boreholes were at a distance such that a vehicle was necessary to get from one to the other, there were issues with radio links between the wells, and there were six separate GPS clocks. In addition, there were six separate sensor systems, six separate data acquisition systems with different file formats—Mirf, TDMS, and SegY—and four service companies—SLB, Silixa, Avalon, and ISTI. All of these issues contributed to the complexity of monitoring. Regarding the sensors, the digital and analogue geophones had similar performance and the BOSS tool was more sensitive than the cemented DAS. Both the BOSS and PSS tools had a high frequency resonance. Like SLB, GES used the checkshot and perforations to calibrate the velocity model and to orient the sensors. Ideally, the velocity model would have been calibrated prior to the stimulation. In preparation for the stimulation GES and the Utah FORGE team held weekly meetings for planning where anticipated issues were discussed and planned for. However, things were still missed. Missed issues included: computational network efficiency, the wireline not meeting specifications, and building of the BOSS string in a clean controlled environment. There were additional issues with the number of detections and file size for the real-time processing. With prompting from Joe Moore, Ben also looked into events from the start of stage 1. From the GES reference catalog, it looked like events did not start immediately. However, with careful reprocessing, several small magnitude events were identified close to the injection zone. This points out the potential importance of the smaller events in the seismic monitoring. In summary, some key lessons from Ben include: (1) Work through the monitoring and data acquisition on paper and in discussion prior to the experiment; (2) Test and assemble everything possible beforehand – Never take a potential problem into the field; and (3) Try to imagine everything that can go wrong. The greatest single problem during the stimulation was wirelines.

DAS Monitoring

The next two talks focused on DAS monitoring. The first talk from David Podrasky, Silixa, focused on the data and catalog generation using the cemented DAS cables in 78-32 and 78B-32. In the second talk, Manuel Mendoza, University of Colorado, described an experiment where he installed ~2 km of DAS at the surface. David began his talk on the cemented DAS recounting some of the issues in the installation of the cable in 78B-32. Originally this cable was to go to reservoir depths but broke during installation. For the stimulation, Silixa was able to record data from the DAS in both 78-32 and 78B-32 by connecting the two wells using a surface cable. The cables were calibrated using a tap test. Triggers were generated using an STA/LTA applied to both wells. The triggers were then manually reviewed. There were 1300 quality-controlled events. The geometry of the cables located above the injection and the relatively shallow depths of the cable provide a poor geometry for constraining locations. Silixa is continuing efforts to refine locations and get magnitudes. There were a few issues regarding the acquisition. Namely, the work with trying to install the geophone chain in 78B-32 caused many false triggers on the cemented DAS in the same borehole. Also, the interrogator was located in the work trailer, which was being used by many individuals. Inadvertent bumping of the interrogator or slamming of the trailer door also created unwanted triggers. David concluded his talk with a strong argument for having DAS in well 16B(78)-32 for earthquake locations and monitoring for frac hits. Ben Dyer noted a high frequency P-ringing and asked if this is seen at other sites. The answer was no.

Manuel Mendoza started by describing the motivation of the surface DAS experiment; it is more cost effective than borehole DAS, is easy to deploy, and may complement other seismic monitoring efforts. The installation of the surface cable was constrained to cleared land and a small trencher was used to get a 5 to 7” trench for burying the cable. The shallow burying of the cable provides surprisingly good signal-to-noise. The cable was laid out in an L-shaped configuration and was anchored at pad 78B-32. The interrogator was located in the processing trailer. While Manuel is still processing the data, he showed some promising examples of recording the vibroseis shots, surface waves from cultural noise, likely coming from the 16A pad, signals generated during stage 2 and 3 perforation shots, a microseism from stage 3, and signal from a local natural earthquake. He also noted some scattered energy that he was investigating to see if it might be related to a topographic or geomorphic feature, like a wash, or perhaps to a fault structure. While more processing is needed, Manuel showed some potential promise for including surface DAS in the monitoring. The data acquisition had some of the same issues as the cemented DAS related to unwanted triggers from the interrogator location. There was also noise introduced into the system where cables had been spliced.

Downstream Monitoring Products

The last set of talks on Day 1 were related to operating adaptive traffic light systems (ATLS) at GES and ETH. In the first talk Falko Bethmann (GES), began with a brief overview of both (GES and ETH) ATLS and then transitioned to the work at GES. GES provided the data feed for the ETH ATLS. GES tracks the incoming earthquake catalog and the injected volume to calculate exceedance probabilities for some maximum magnitude. Falko pointed out many of the issues faced in producing the real-time data streams needed for ATLS. Some of the specific issues were loss of communication between well sites because of weather, changes in the hydraulic data streams, different reference time zones, changing of instrumentation between stages leading to different network sensitivities and location accuracy, temporal changes in magnitude of completeness, and keeping the data processing, detection and location, in near-real-time. Some lessons that Falko identified include the importance of running ATLS on-site, knowing the bottlenecks in the processing system, processing the data at different trigger levels, and defining clear interfaces that can be adapted to last minute changes. The second part of Falko’s talk addressed the question of how many events are needed to achieve a stable *b*-value. *b*-value is a key parameter in ATLS calculations. For this analysis, Falko used both maximum likelihood and *b*-positive. For this analysis, he created a synthetic catalog, which included potential errors in the magnitudes. The results depended on method (maximum-likelihood or *b*-positive), but in these initial calculations it seems that one needs ~1000 events to get a *b*-value with acceptable error bars. In conclusion, the FORGE 2022 stimulation provided valuable insights and experience on how a data set evolves and how forecast methods behave using an imperfect data set.

In the second talk, Federica Lanza (ETH) described the ATLS system that was run at ETH. The work being done at ETH is part of the Geothermica DEEP project. Federica provided a comprehensive description on the differences between a traditional traffic light system, which only defines the extremes with no underlying physical modeling, and an ATLS. The ATLS are dynamically updated, forward looking, and are full probabilistic risk models. A key component of the ATLS is to use Bayesian updating where the a priori assessment is updated as data from the seismic network and hydraulic monitoring and other potential data are used to reduce the a priori uncertainties. The ETH ATLS is optimized when using a SeisComP system, although it can work with a fdsnws/event standard web service. The different forecasting models are run within the RT-RAMSIS framework (**R**eal **T**ime **R**isk **A**ssessment and **M**itigation for Induced **S**eismicity): a controller for real-time (or playback) time dependent seismicity, seismic hazard, and risk assessment. The stimulation at Utah FORGE was a real-time test of this system. A data exchange for the stage 3 stimulation was established between GES and ETH. Unfortunately, the data stream was lost early into the stimulation, but the testing of the ATLS from the beginning of stage 3 produced very positive results. The last full forecast predicted ~1000 +/-700 events with a magnitude above M -1.48. There were 1213 events above M -1.48 in the GES catalog. There were some identified issues related to changes in the stimulation plan compared to what ETH was expecting. It was also noted that the system cannot handle data gaps. Federica also presented results from ATLS testing at Bedretto. Some questions that need to be addressed include how to handle data gaps, how much data is needed, and how to deal with issues related to magnitude uncertainties. There was going to be continued analysis of the Bedretto and Utah FORGE datasets, including a playback of the Utah FORGE 2022 stimulation data. It was noted in the discussion that the forecasting models implemented in the ATLS do not consider complex interactions that can lead to seismic events months after the stimulation. However, the models do currently simulate a seismicity rate decay limited for the post-shut-in phase. The decay behavior is very site dependent and its initial parameters can be quite unconstrained. A calibration, usually with data from the post shut-in phase itself, is therefore required.

Surface Seismic Monitoring

On day 2, the talks were focused on additional experiments conducted during the 2022 stimulation. There were three talks given in person and two were presented remotely. In the first talk, Kris Pankow (UUSS), presented the catalog generated through routine operations, the traffic light system that was in use during operations, and efforts to generate a microevent catalog using the Utah FORGE local seismic network. Kris noted that in advance of the stimulation there was a swarm of small earthquakes in the Mineral Mountains near the Blundell Power Plant. This swarm ceased before the stimulation and a few events occurred after the stimulation. She noted that it was lucky that the swarm ceased in advance of the stimulation and we did not have to discriminate between seismic source zones. The majority of the talk was devoted to a study by recently graduated undergraduate student Alex Dzubay who used the 11 events detected and located with the local network as templates for a matched filter analysis using data primarily from station FORK. Kris described the quality control efforts and how the 2019 stimulation was used to calibrate the magnitudes. In the first pass of the matched filter, the template catalog was increased from the initial 11 events that occurred during stage 3 to 38 templates (7 stage 1, 6 stage 2, and 25 stage 3). Using the revised template catalog, over 1300 detections were found and 735 met the quality control criteria (29 stage 1, 26 stage 2, and 680 stage 3). The magnitude of completeness was Mc -0.7. This compared to the GES catalog of 2409 events with an Mc -1.3. There are differences in the magnitude calculations between the two catalogs that are being examined as part of ongoing work. In a waveform-based clustering analysis, events from stage 1 and 2 clustered together and events in stage 3 form 4 separate clusters. The next phase of this project is getting locations. This study suggests the potential value of multiple shallow (1000') boreholes.

In the second talk Gesa Petersen (UUSS) described the initial data analysis of a ~200 geophone deployment. The three-component geophones were deployed in 13 patches of 16 geophones (4 x 4 sensors) with 30 m spacing from April 4 – 6 through May 5 – 6. Data from each patch was stacked to form one high signal-to-noise trace per patch. Spectral analysis of the larger events found that the peak signal energy is in the band from 20 to 40 Hz with signal up to 100 Hz. The traces are noisy below ~15 – 20 Hz. Using the stacked, filtered traces Gesa applied a characteristic function and back projection on a spatial-temporal grid for event detection and preliminary location. The number of resulting detections is a function of the characteristic function threshold. Gesa showed clear examples for detecting microseisms with magnitudes M -0.2, -0.01, -0.4, and -0.7. These events were visible on both vertical and horizontal components. Using this detection threshold, Gesa processed 10 hours of high microseismic activity during stage 3. In comparisons with the GES catalog, Gesa showed that using a characteristic function threshold > 70 that she reliably detects events with magnitudes M > -0.6. At this level and using locations from the GES catalog the spatial patterns in the GES catalog are suggestive, but lack the density of events for meaningful interpretation. The full detection catalog (lower characteristic function values) would better capture the spatial distribution, but also introduces more false detections. Continued work is being done to lower the detection threshold and automatically identify false detections. Gesa also presented five preliminary P-wave first-motion focal mechanisms for the larger events from stage 3 determined from the stacked traces. While stressing that these are preliminary, Gesa noted the overall similarity in fault plane orientation and sense of slip. Work is continuing to add S/P ratios to better constrain these mechanisms. In discussion, it was noted that it would be interesting to look at the stacks from subsets of the patches, 2x2, 3x3, to establish how many stations are needed.

In the final in-person talk Hongrui Qiu (LBNL) presented initial results for the processing of the VSP survey that was conducted at the end of the 2022 stimulation. This work is also part of the Geothermica DEEP project. The VSP survey was conducted using a vibroseis that followed the road with shot spacing of 30 m. The shots recorded on the cemented DAS in 78-32 and 78B-32 and the geochains in 58-32 and 78B-32. Hongrui showed several examples of the data collection on the different sensors. Generally, the DAS was noisier, but the P-waves are still clear. The motivation for the VSP is to get an improved velocity model. Hongrui also presented related work, where the LBNL group is reprocessing the 2D and 3D reflection seismic data that was collected at Utah FORGE. In this work, they are using machine learning and frequency-dependent travel times to pick the over one million first arrivals. Using these first-arrivals they are constructing P-wave tomographic velocity models. The preliminary results show fine-scale detail from the surface to 625 m depths. In a third analysis, reverse time migration is applied to the VSP vibroseis shot gathers. Using the combined datasets and processing techniques the goal is to get a refined detailed P-wave velocity model for the Utah FORGE study area. There is currently lateral heterogeneity not accounted for in the existing models. Next steps include applying migration and tomography to the VSP data.

The last two talks were given remotely. The first of these by Jonathan Ajo-Franklin (Rice University) described a project called FOAL (FORGE Observation Array Linear). This project aims to address the question if we can use microseismic energy as a source for seismic imaging of EGS systems using surface arrays. Jonathan designed a surface geophone experiment to target the P-to-S conversion phase evident in the DAS data. The goal is to apply reverse time migration to both P and P-to-S conversions. This should allow for better imaging of the properties at the bedrock to alluvium interface, where the P-to-S conversions are generated. The experiment used 100 Smart Solo geophones in a linear array extending west of borehole 16A(78)-32 to east of borehole 78B-32. These geophones were deployed in 3 – 6" holes with interstation spacing of < 40 m. The linear array was designed to roughly follow the surface projection of the deviated section of borehole 16A(78)-32. The geophones were programmed to record from April 10 to May 10. Initial processing indicates strong surface waves generated from pumping activities and a clear diurnal noise signal. The geophones are nosier than the surface broadband station FOR2 that is part of the local seismic network. It was also noted that there was poor recovery of signal in the microseism band. Regarding seismic event detection, Jonathan showed examples of a local tectonic earthquake and for microseisms related to the stimulation. Initial estimates show a detection threshold of M -0.2. Importantly, it does appear that both the P and P-to-S conversions are seen in the data. Processing will continue. Some lessons noted include tighter spacing of the geophones to account for spatial aliasing as a result of high frequency culturally generated surface waves and it might be difficult to get a catalog of events without more sophisticated detection algorithms. As a follow-up to the DAS discussion from the prior day, Jonathan also presented details on the DAS cable that will be installed in borehole 16B(78)-32.

The final talk was given by Stuart Farris (Stanford University). Stuart described an experiment designed to test a new sensor, Sercel QuietSeis chip. These sensors use MEMS technology and 12 sensors were buried and recorded data during the Utah FORGE stimulation. These sensors are relatively inexpensive and could be an option for dense deployments. A subset of the sensors was collocated with other sensors for comparisons. The results of this analysis showed that these new sensors were more sensitive than the geophones in the 0 – 10 Hz band and had a similar performance to the geophones at higher frequencies.

Future Seismic Monitoring

The meeting concluded with participants breaking into four groups to help summarize what was learned and to provide suggestions for future monitoring. Each group was asked to address the following questions: (1) What was learned? (2) What additional research is needed? (3) Recommendations for future monitoring at Utah FORGE and (4) Recommendation for monitoring of EGS more generally. After the four groups had time to discuss, each group presented to the full group for comment and discussion. There was significant overlap between the discussion and recommendations from each group.

What was learned?

Overall, the seismic network design met the goals of the 2022 stimulation. Both detection limits and location accuracy are sufficient for planning the location of the second deviated well. The borehole systems were necessary for establishing the detailed high-precision catalog and can be used in future studies to determine necessary detection limits and location accuracy.

Current geophone and wireline technology do not meet the specifications stated by the manufacturers. Experience with these systems at Utah FORGE indicates that it is unrealistic to push the current tools above 180°C. To go to higher temperatures, other tools should be investigated such as the Avalon BOSS tool.

For the adaptive traffic light systems variable injection scenarios need to be implemented into the workflow, as does ways to deal with data gaps.

There were three service companies, plus Manuel Mendoza (CU), GES and Utah FORGE personnel all working in a single trailer. The crowding in the trailer combined with traffic for using the kitchen and bathroom caused the interrogators to be bumped and unwanted triggers to be generated. Additionally, there was no one specifically in charge of coordinating all the seismic operations and some groups were not fully informed of timing and changes in operations.

What additional research is needed?

Research should be devoted to developing and testing high temperature seismic sensors. Some key questions that were identified include: how long can the current geophones last at 160°C and what is the long-term performance of the BOSS tools at temperatures above 180°C? It was also suggested to test the use of coils to pump water to cool tools.

In the analysis of the seismic tools and sensors a comparison of the noise levels of the different seismic instruments and network designs needs to be performed.

Research should also be focused on how to integrate all of the data into the real-time monitoring. For example, can the horizontal and vertical DAS installations be combined, can the full DAS data streams be integrated in real-time processing and how can data from surface geophone deployments be telemetered and integrated?

Since machine learning (ML) techniques have been proven efficient in detecting earthquakes (including micro-earthquakes) and picking their phase arrivals, it is suggested to conduct more research to promote the utilization of ML for real-time seismic monitoring in EGS.

There is a need for a Utah FORGE Community Velocity Model that is available to all groups and a set of ground truth events.

Separate from operational research, more research should be directed towards the level of precision needed to map fracture growth and if waveform clustering could help to define fracture networks, if we can distinguish wet and dry fractures, and what is the role of tremor/aseismic signals in mapping fluid movement in fractures? Additionally, can we get moment tensors for the smaller events and what does that tell us about the development of the reservoir and the migration of fluids.

For advanced traffic light systems, research should focus on using playback modes to test how the ATLS performed and how changes in network sensitivity and data gaps affect the forecasts. Additional research is needed to develop a variety of models to capture different aspects of the stimulation. These different models could compete between each other in playback mode to help better inform the ATLS. Similarly, there could be competing streams of data and the ATLS could revert to the most preferred data stream to maintain a robust forecast. Work also needs to focus on how many events are needed for ATLS to work and what is the tolerance for error in magnitudes. ATLS should also be expanded beyond stimulation to provide forecasts for production and shut-in periods.

Recommendations for future monitoring at Utah FORGE

For optimal monitoring, those providing real-time monitoring (e.g. generating earthquake catalogs and running traffic light systems) need to be on-site. Additionally, there needs to be an operational manager that is responsible for integrating the seismic groups and a wireline engineer that works for Utah FORGE. During stimulation the operations manager should be located in the frac truck to communicate back to the seismic monitoring trailer. It is recommended that the Utah FORGE seismic team have two trailers available for seismic monitoring, one dedicated to seismic monitoring equipment with enough workspaces to house each group processing the real-time data, and a second with a bathroom, kitchen, space for additional personnel to work, and for meetings.

In preparation for seismic monitoring, some key elements should be decided in the planning stage before arriving at the field. All groups, both the seismic and hydraulic, participating in monitoring should participate in this aspect of the planning. Specific items to be decided on include the reference time and any potential timing issues and details of data integration and file formats. Additionally details regarding the ATLS should be established with the operations team. The expectations for the ATLS should be established and there should be a process to decide the probabilistic thresholds (e.g. exceeding probability of a felt/damaging event or as a function of nuisance). The ATLS groups should also test the sensitivity of the system for the minimum amount of data needed, given the variety of datasets. Importantly a plan for exchanging data and communicating between the different groups needs to be established and tested in advance to the stimulation activity.

Regarding seismic monitoring design, it was noted that Utah FORGE is a research facility and as such the seismic monitoring from the 2022 stimulation is a minimum, “do not do less”. It is important to have the very complete catalogs to help guide monitoring at projects that might not be able for logistical reasons to have a deep borehole network. The specifics of the network design should address the operational needs for the activity being monitored but should include seismic monitoring in the deep boreholes supplemented with additional surface monitoring. It was noted that additional geophone arrays should include real-time telemetry options. It was also recommended that borehole geophones be installed to depth in advance of the stimulation.

Specific suggestions for seismic monitoring included using a chain of 200^{o}C BOSS tools for deep monitoring in one of the deep boreholes, analog PSS tools installed at reservoir depth in the other two deep boreholes, and a network of surface geophone patches that are telemetered. This seismic network would be enhanced with DAS in borehole 16A/B(78)-32, the cemented DAS in 78-32 and 78B-32, and surface DAS that has several cables installed in a star pattern. The DAS in the deviated borehole could include disposable DAS that is dropped into the hole.

In the actual implementation of the ATLS there should be a mechanism to feedback information from the ATLS into the injection scheme providing for a dynamic optimization of the injection strategy. There should also be a means to incorporate more uncertain data with low weight for example when triggering rates spike and there is more latency in the data.

Recommendation for monitoring of EGS more generally

A consensus across the four groups was that three deep boreholes is not necessary. However, having at least one deep borehole, as seen from stage 1, provided a reasonable detection threshold and good locations. As noted in the recommendations for Utah FORGE, the objectives of the seismic monitoring should be defined and the network designed on that basis. The multiple datasets at Utah FORGE could help to inform what combination of instrumentation would meet the goals of a commercial project.

It was also recommended that a best practice for creating and operating ATLS be developed to help for future commercial implementation.

Table 1. *Participants*

Seismic Monitoring Partners	Observers/Advisors
UUSS (Pankow, Whidden, Petersen, Bradshaw, Wells) ***GES*** (Dyer, Bethmann, Karvounis, Meier) Santa Fe Seismic (SFSeis) (Rutledge) ***ETH*** (Lanza, Shi, Ciardo) ***SLB*** (Martinez, Borchardt) ***Silixa*** (Podrasky) ***Rice*** (Ajo-Franklin*) ***Univ of Colorado*** (Mendoza, Sheehan) ***LBNL*** (Qui) ***Stanford*** (Farris*)	***Utah FORGE PMT*** (Moore, McLennan, Podgorney, Simmons) Seismic affiliated STAT members (Eaton, Shemeta)

*Presented remotely