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The Amplify Monitoring Team: Initial Design, Development, and Deployment of Seismic Monitoring Systems for Near-Field EGS Well Stimulation

Michelle Robertson[1], Jiann Su[2], J. Ole Kaven[3], Chet Hopp[1], Evan Hirakawa[3], Erika Gasperikova[1], Patrick Dobson[1], Paul Schwering[2], Nori Nakata[1] and Ernest L. Majer[1]

[1]Lawrence Berkeley National Laboratory, [2]Sandia National Laboratories, [3]United States Geological Survey

EGS, enhanced geothermal, stimulation, seismic monitoring, microseismicity, induced seismicity

ABSTRACT

The DOE GeoVision study identified that Enhanced Geothermal Systems (EGS) resources have the potential to provide a significant contribution toward achieving the goal of converting the U.S. electricity system to 100% clean energy over the next few decades. To further the implementation of commercial EGS development, DOE's Geothermal Technologies Office (GTO) initiated the Wells of Opportunity (WOO) Amplify program, where unproductive wells in selected geothermal fields will be stimulated using EGS technologies, resulting in increased power production from these resources.

As part of the WOO-Amplify project, GTO assembled the Amplify Monitoring Team (AMT), whose role is to develop, install and operate seismic monitoring systems in the near-field EGS setting. This team, consisting of scientists and engineers from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL), and the US Geological Survey (USGS), is working with WOO-Amplify EGS Operators Ormat, Cyrq, and OU-Coso to design, develop, and deploy optimized seismic monitoring systems at five geothermal fields where WOO-Amplify well stimulations are planned: Don A. Campbell (NV), Tungsten Mountain (NV), Jersey Valley (NV), Patua (NV), and Coso (CA).

Using geologic and geophysical field data provided by the WOO-Amplify teams, the focus of the AMT is to develop advanced simulation and modeling techniques, design targeted seismic monitoring arrays, develop innovative and cost-effective methodologies for drilling seismic monitoring boreholes, deploy effective seismic instrumentation, and facilitate the use of microseismic data to monitor well stimulation and flow within the geothermal reservoir. Realtime seismic data from the five WOO-Amplify sites will be streamed to a publicly accessible Amplify Monitoring website. AMT's advanced simulations and template matching techniques applied during pre-stimulation phases can help improve understanding of potential seismic hazard and inform the Operator's Induced Seismicity Mitigation Protocol (ISMP).

** Authors from SNL and USGS will be confirmed following internal reviews of this manuscript by Sandia and USGS*

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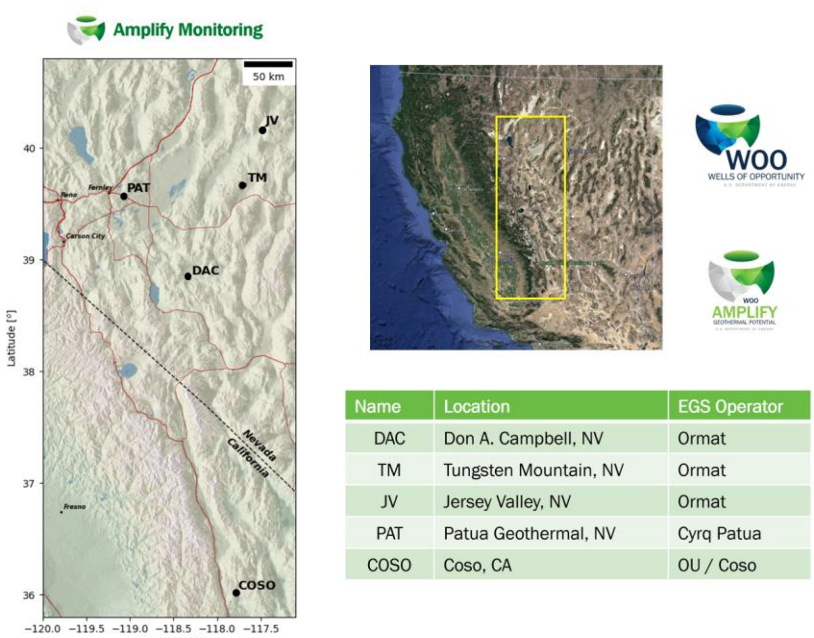
Over the next two years, AMT will be drilling, instrumenting, and recording seismic data at the WOO-Amplify field sites, telemetering the seismic waveform data to AMT's central processing system and providing the processed location data to the WOO Amplify Operator teams. These data and monitoring systems will be critical for effective monitoring of the effects of planned well stimulation and extended flow tests during the next stage of the WOO-Amplify project.

1. Introduction

Enhanced Geothermal Systems (EGS) commercial operators need cost-effective procedures for seismic monitoring of near-field EGS reservoirs with characterization methods that can provide the highest priority data at the scales necessary to define crucial reservoir properties. Although reservoir creation and management are critical, attention must also be paid to deploying and operating monitoring systems to address public and regulatory acceptance and meet Induced Seismicity Mitigation Protocols (ISMP) (e.g., Majer et al., 2012). An affordable monitoring system with data acquisition, visualization, archiving, and the means to communicate with the public as well as informing the commercial operators in real time is essential for effective EGS monitoring.

In late 2020, the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) launched the Wells of Opportunity (WOO) Amplify demonstration project with the objective of improving the performance of low-permeability or underproductive near-field geothermal wells using advanced EGS stimulation techniques. Five EGS sites were selected for the WOO-Amplify project (Figure 1). Four sites are in the Basin and Range Province of western Nevada: Don A. Campbell (DAC), Tungsten Mountain (TM), Jersey Valley (JV) and Patua (PAT). DAC and PAT are located along the tectonic margin between the Walker Lane Belt and the Basin and Range. The fifth site at Coso (COSO), is in southern California – tectonically on the south end of the Walker Lane, near the margins of the Sierra Nevada Batholith and the Eastern California Shear Zone.



Name	Location	EGS Operator
DAC	Don A. Campbell, NV	Ormat
TM	Tungsten Mountain, NV	Ormat
JV	Jersey Valley, NV	Ormat
PAT	Patua Geothermal, NV	Cyrq Patua
COSO	Coso, CA	OU / Coso

Figure 1. Locations and EGS Operators of the five WOO-Amplify geothermal field sites.

As part of the WOO Amplify project, GTO also initiated the Amplify EGS Near-Field Monitoring and Characterization project, or Amplify Monitoring, charged with developing a low-cost standardized methodology for monitoring stimulations at the WOO-Amplify sites to provide the data most needed by EGS operators for successful commercial reservoir stimulation. Amplify Monitoring is a joint effort of scientists and engineers from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL) and the U.S. Geological Survey (USGS), collectively called the Amplify Monitoring Team (AMT).

The Amplify Monitoring project has three phases of monitoring for each of the five WOO-Amplify sites. Phase 1 focuses on the pre-stimulation tasks of modeling and simulations, background data acquisition, monitoring array installations, and data streaming to our Amplify Monitoring website. Phase 2 covers the timeline just prior to and during stimulation where AMT will stream realtime waveforms to operator-specific network interfaces, provide automated seismic locations and magnitudes, and provide additional data streaming if needed for temporary high-resolution or multilevel monitoring arrays. AMT will continue operating the monitoring arrays during the post-stimulation Phase 3, including data streaming access and seismic data analysis. Data and results from each of these phases will be shared and discussed with the individual Operators to inform their ISMP and EGS Best Practices protocols, and update 3D subsurface models (Figure 2).

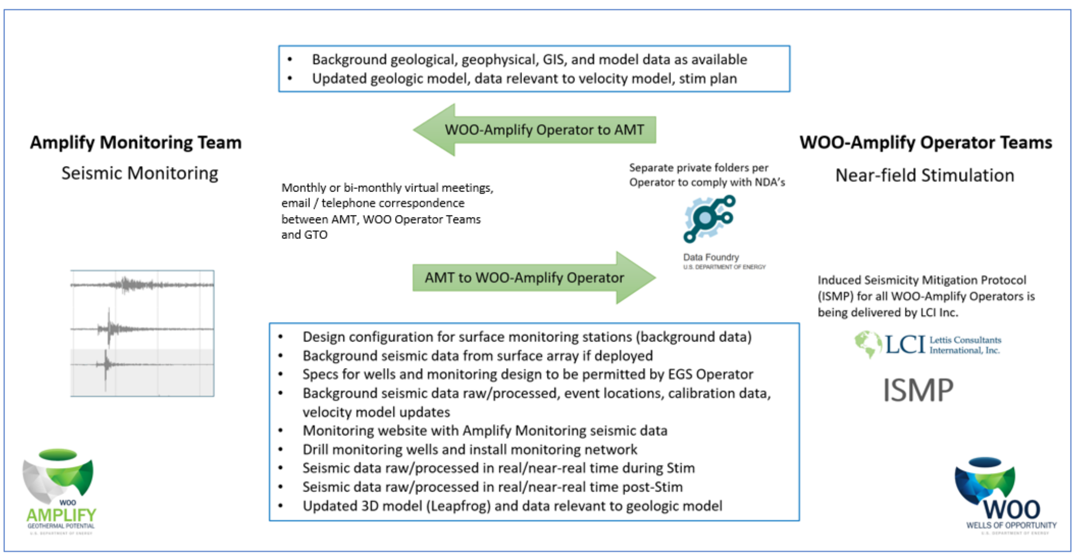


Figure 2. Collaboration and information exchange between AMT and WOO-Amplify EGS Operators.

Amplify Monitoring project timelines are necessarily in step with the WOO-Amplify Operator stimulation schedules at the five proposed stimulation sites. We are currently in Phase 1 for DAC, TM, JV and PAT, and we are ready to drill at DAC following completion of the requisite permitting. Stimulation well site selection at COSO is currently under evaluation. The final result of our project will be individually optimized seismic monitoring arrays installed and operating at each of the five WOO-Amplify sites with raw and processed seismic data streaming from the arrays in real-time via our Amplify Monitoring website.

In this paper, because the Amplify Monitoring project is in the early stages of Phase 1, we focus on the site characterization, initial modeling and simulations, background data acquisition, and monitoring array design for the first WOO-Amplify stimulation site DAC.

2. Site Characterization

Geothermal resources often are found in regions where high strain rates and preexisting faults and fracture systems are co-located (e.g., Majer and McEvilly, 1979; Faulds and Hinz, 2015). Understanding the occurrence, frequency, and potential magnitude range of seismicity in these regions can aid resource development by identifying actively deforming zones of heat and fluid flow and assessing the potential for inducing seismicity.

2.1 Expanding Seismic Catalogs using Regional Seismicity

In geothermal areas that experience natural seismicity, expanding our existing catalogs of microseismic activity using regional public seismic networks can reveal more detailed fault and fracture structure, or at the very least the predominant orientation of existing fault systems (e.g., Stark, 1992; Kaven et al., 2014). While some geothermal resources experience little seismicity, tectonic faults in the vicinity of those resources can be critically stressed and may host significant magnitude seismicity. Thus, expanding regional seismicity catalogs in lower seismicity areas can improve seismic hazard assessments and ensure safer operation of geothermal resource exploration related activities. One common approach to expanding existing public seismicity catalogs is to use template matching or matched filter detection, which utilizes waveforms from existing recorded events, convolves those waveforms with continuous records at the same station, and identifies additional, smaller magnitude events within the seismic record. These methods have yielded vastly more seismic events in a variety of settings (e.g. Skoumal et al., 2019).

For the Amplify Monitoring project, we applied the template matching approach to expand the local seismic catalogs at the four WOO-Amplify sites in Nevada: DAC, PAT, TM, and JV (Figure 1). Note that owing to their proximity we combined our template matching effort for both TM and JV. Continuous data downloaded from the Incorporated Research Institutions for Seismology (IRIS) waveform archive was processed locally on high performance computing resources. We then resampled the data to filter for template events and continuous waveforms between 5-15 Hz, and designated template matches when the Network Normalized Cross-Correlation Coefficient (NNCC) was 10 to 15 times the daily median absolute deviation (MAD) of the NNCC (depending on the site). Finally, we estimated magnitudes using average relative amplitude measures of the template and matched events for each waveform pair per event (Schaff and Richards, 2014).

In general, the higher the MAD detection threshold, the more reliable the matches will be. Also, using higher MAD thresholds ensures that automatic phase identification is more accurate and manual picking of phases can be avoided. However, the matches do require some measure of manual inspection to ensure their quality. We assume that matched event locations are within a varying (but small) distance from the template events locations. All aforementioned methods are standard template matching methodologies and have yielded reliable extended catalogs in many settings.

Using our template matching approach, we increased the event count at PAT from 219 to 978 additional events with reliable magnitude estimates, and at DAC we expanded the local catalog from 149 events by 254 matched events with reliable magnitude estimates (Figure 3). At TM and JV, we are still in the process of detecting additional events using 462 templates in the greater area. These extended catalogs are utilized in seismic hazard assessments for each site and significantly improve our understanding of the occurrence of seismicity, observed magnitude ranges, and potential seismic hazard at the various sites.

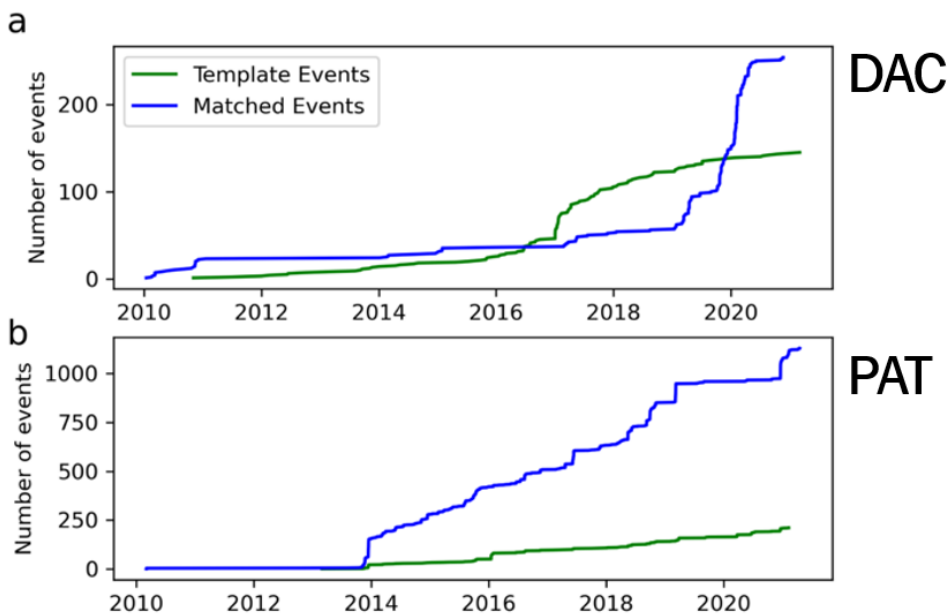


Figure 3. Template matches at a) Don A. Campbell (DAC) and b) Patua (PAT) geothermal fields. Green lines indicate the cumulative number of template events used. Blue lines indicate cumulative number of matched events.

2.2 Noise Analysis from Local Seismic Monitoring Stations

To provide input for our simulations and to quantify noise levels at the WOO-Amplify sites, we are currently analyzing seismic data from our short-term monitoring stations. At the three sites without a previously existing seismic monitoring array (DAC, TM and JV) we installed one 3C surface sensor on hard rock (ROK) and one 3C sensor on top of basin sediment fill (SED), and we are collecting continuous data on solar-powered recording systems (Figure 4). The fourth site (PAT) had five existing borehole geophones from a previously installed array (2012-14) that were still usable for background data collection in basin sediments, and we added surface 3C geophones for a total of six recorded channels per station. The fifth Amplify site (COSO) is currently on hold, pending the final selection of the stimulation well by the WOO-Amplify Operator team.

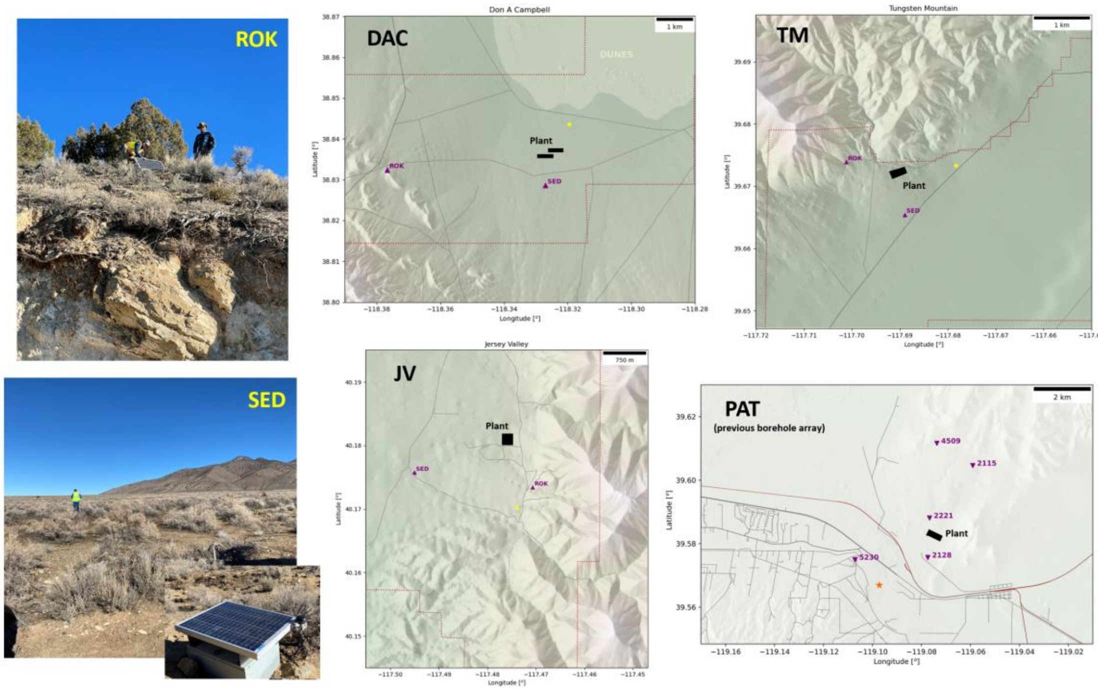


Figure 4. Field photos of ROK and SED installations at JV (left) including the solar-powered recording system, and map views of background monitoring station locations for DAC, TM, JV and PAT geothermal sites (center and right). Upward facing triangles are newly installed surface seismic monitoring stations; downward facing triangles are pre-existing borehole seismic monitoring stations, and stars are wellhead locations of proposed WOO-Amplify stimulation wells.

The surface 3C seismic stations ROK and SED at DAC have been recording for over a year, the five 6C stations at PAT have been recording for nine months, and the ROK and SED stations at TM and JV were recently installed and are awaiting data collection. Noise analysis results for DAC are shown as power spectral densities in Figure 5. Note that all data recorded in the time period indicated is used in these plots without attempting to detect and remove earthquakes.

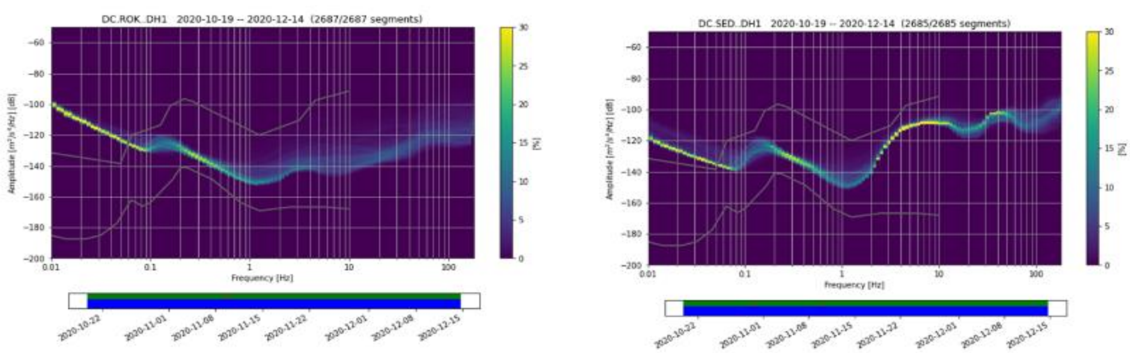


Figure 5. Probabilistic power spectral densities of continuous data recorded at station ROK (left) and SED (right) on channel DH1 (vertical) near the DAC geothermal field. Grey lines indicate the global low and high noise models (Peterson, 1993). The bar below each plot indicates the data availability (green if available, red showing gaps).

The noise analysis results show that DAC station SED (on valley sediment fill) has higher noise levels, albeit more focused for frequencies greater than 1 Hz compared to DAC station ROK (on hard rock). The greater spread of noise on station ROK is likely related to less attenuation of higher frequencies on the hard-rock station compared to station SED as simple source models that include attenuation indicate. Additionally, noise from the plant and its operation is likely contributing to the higher noise at frequencies greater than 1 Hz.

Noise analyses for the five PAT stations in valley sediment fill are shown in the ~one-month power spectral density (PSD) plots in Figure 6, where results show that the surface geophones have higher noise levels than the ~100m deep borehole sensors, and the surface sites vary in noise depending on the distance from the plant. PSDs for earthquakes of various moment magnitudes (Mw) were modeled using the approach of Abercrombie (1995). These are shown as dotted lines of different colors to illustrate the detection capabilities of sensors with different noise floors in relation to the expected magnitudes of seismicity. Note that the borehole sensor at station 4509 is not functioning correctly (hence its low noise) and has since been removed from the background monitoring network.

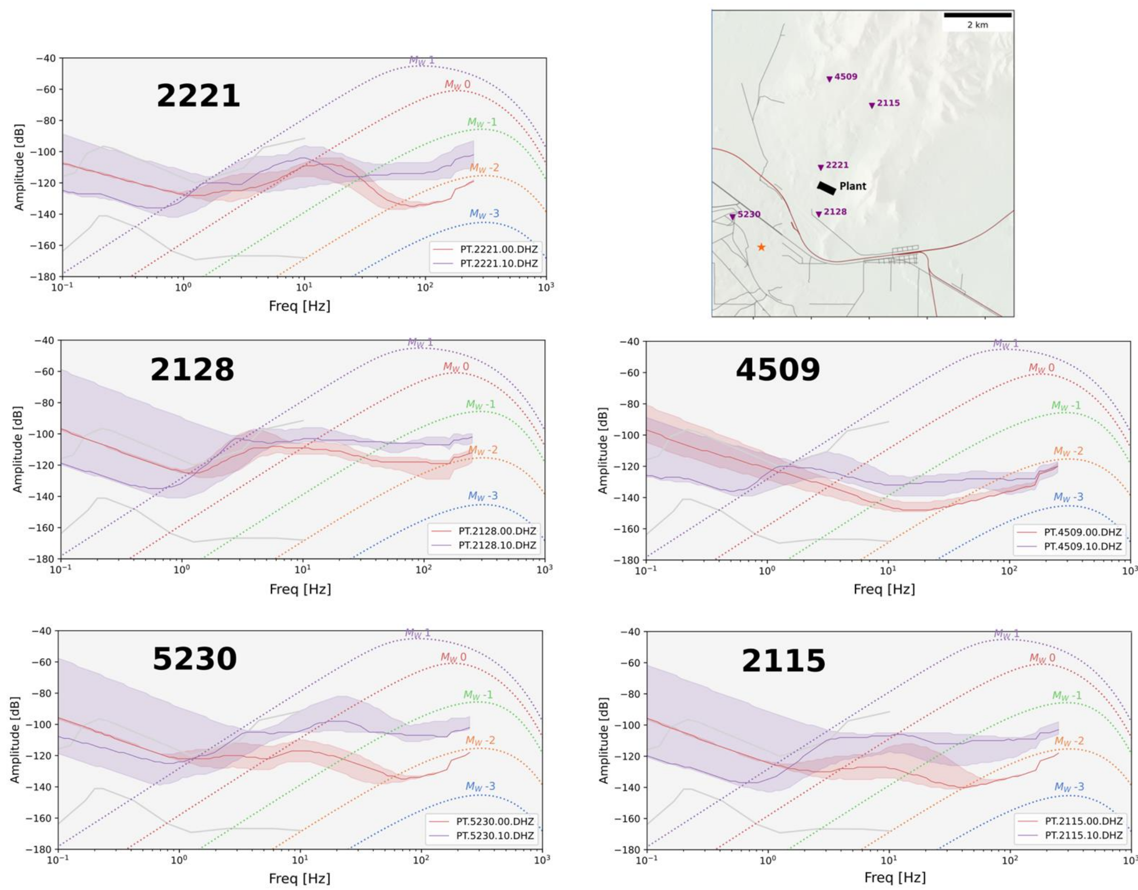


Figure 6. Median PSD plots for five Patua stations from roughly one month of continuous data collection. Borehole sensor PSDs are red, while surface PSDs are purple. Shaded regions surrounding the median signify the 10th and 90th percentile of the PSDs. Dotted lines show modeled PSDs for earthquakes of different magnitudes at an event-station distance of 1 km (stress drop: 1 MPa, Q: 100). For reference, the gray lines are the Peterson New High and New Low Noise Models (Peterson, 1993). Station locations are indicated on the map in the upper right (purple inverted triangles).

Attenuation is often quantified by the quality factor Q as an analog to a damped, harmonic oscillator where small values of Q refer to large attenuation and vice versa. Near-surface conditions, especially unconsolidated alluvium, can have significant attenuation, thereby suppressing the detectability of seismic energy emanating from a local microseismic event. Brune spectra (Figure 7) for simple point sources at the same distance with different attenuation values, Q, reveal that highly attenuative material (Q=50) reduces the resultant recorded velocity amplitude by about half an order of magnitude when compared to less attenuative material (Q=200). Note also that the maximum velocity amplitude is observed at lower frequencies for more attenuative material.

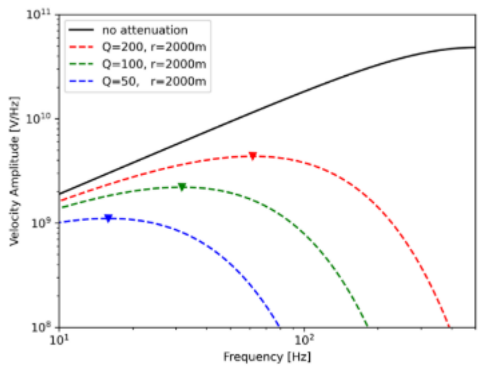


Figure 7. Brune spectra for 2000m source-receiver distance and varied attenuation factors, Q. Triangles indicate maxima for each curve. Additional model parameters for this plot are M=-1, stress drop = 5Mpa, Vs=2000m/s.

These results clearly indicate the need for local monitoring prior to a full network installation as noise levels vary widely in complex geologic settings. All of the Amplify-WOO sites share very complex geologic conditions and, in particular, the Nevada sites all share highly attenuative near-surface geology due to the presence of thick basin fill.

We have also begun an effort to quantify the near-surface attenuation using our recordings at the hard-rock and valley fill sites using regional seismic events at epicentral distances less than 70km and measuring the changes in the rise time of the initial pulse. Changes in the rise time occur due to the dispersion of the seismic signal as it propagates through the attenuating medium (Gladwin and Stacey, 1974). While our results are preliminary at best and subject to large scatter, we do detect a lower quality factor Q, or higher attenuation, at DAC station SED compared to the hard-rock site ROK. This ongoing work will guide our understanding of the local attenuation structure and further informs our full waveform modeling.

3. Modeling and Simulations

As part of the collaboration between the AMT and WOO-Amplify teams, WOO plant Operators are sharing proprietary subsurface data with AMT for use in our modeling and monitoring tasks. Files uploaded by the Operators to private Amplify Data Foundry folders include well logs, temperature logs, 3D digital models (e.g., Leapfrog or Rhino 3D), well locations and trajectories, fault surfaces, lease boundaries, as well as the location of the proposed stimulation well and the planned stimulation depth.

3.1 Source Model

To provide insight into expected seismic waveform recordings at DAC and the other WOO-Amplify sites we use SW4, a physics-based seismic wave propagation software (Petersson and Sjogreen, 2017), to produce synthetic seismic waveforms that can be used in convolution with assumed noise signals. These simulations are valuable because they can account for complex interaction between seismic sources, raypaths, and site effects.

For our simulations we choose a source-time function (STF) that excites high-frequency seismic motions typical of microseismic events related to geothermal systems. Since attributes of the STF can alter the shape of seismic waveforms recorded at distant sites, it is important to characterize the STF at specific geothermal sites once more data has been obtained. For initial tests we use a SW4 built-in 'tailed' function which releases most of the moment earlier in the slip duration (Figure 8a). For all simulations here, we choose the width (rise time) of this function so that the corner frequency is around 50 Hz (Figure 8b) and we implement this STF as a moment rate on a 90-degree dipping strike-slip fault at a single grid point (i.e., a point source) at 2 km depth, with magnitude Mw -2.

When we test this source in a simulation using a simple 1D velocity structure and record synthetic motions in a circular array (Figure 8d), some important characteristics of the seismic wavefield are clear. At Station 1 (Figure 8c), located in the strike-perpendicular direction, motion is entirely polarized in the transverse direction, indicating that these are S-waves, while radial and vertical motions are very low. Conversely, radial and vertical motions (VR and VZ) are much larger at Station 2 which is aligned along the 45-degree azimuth, indicating P- and Rayleigh waves, while transverse motions are low. These observations follow directly from fundamental principles related to the strike-slip radiation pattern.

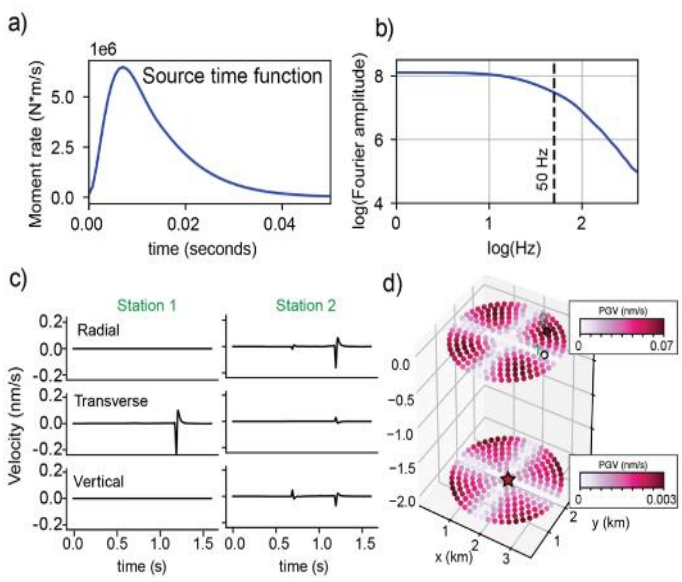


Figure 8. a) Source time function used in SW4 simulations. b) Amplitude spectrum of the source time function. c) Motions at two stations labeled in (d) in a test model using a very simple velocity structure. d) Synthetic ground motion intensity or peak ground velocity (PGV), vertical component only, recorded in dense circular arrays at the surface and at the hypocentral depth. Dots are placed at station locations and are colored based on PGV.

Measuring peak motions at each station in the dense circular array surrounding the source also records the azimuthal variability in motions due to the radiation pattern; we visualize this by coloring each station by their peak vertical ground velocity (PGV). PGV is azimuthally periodic in a four-quadrant pattern across the array which is directly associated with the strike-slip focal mechanism. PGV in the vertical component is highest along the directions of the compression or tension axes (e.g., at Station 2). Motions at the center of the seismic array are very small despite proximity to the source, which is because of another P-wave node in the focal mechanism.

3.2 Velocity model at DAC

Using a 3D surface provided by DAC site operator Ormat representing the top of bedrock derived from well logs (Figure 9a), we can adapt our elementary analysis to account for realistic geology and subsurface seismic velocity structure.

We generated a simple two-layered velocity model for use in our simulations, where depth to bedrock is variable and relatively low velocity Quaternary sand-rich sediments overlie higher velocity volcanic bedrock (Delwiche, 2013). We discretized the model domain by considering a 3D grid with 25 m spacing, encompassing a 6.4 x 6.4 km area around the geothermal site, and extending from the ground surface to 2.5 km depth. All grid points above the bedrock interface are labeled as “sand”, all grid points below this are labeled “volcanic” (Figure 9b). Each grid point is then assigned material properties by rock-type-specific, depth-dependent velocity relations (Figure 9c from Brocher, 2005). Note that at all depths, volcanic rocks have much higher velocity than sand. The result is a velocity profile that increases with depth and has a sharp increase in velocity at the bedrock interface (Figure 9c, right panel, and Figure 9d).

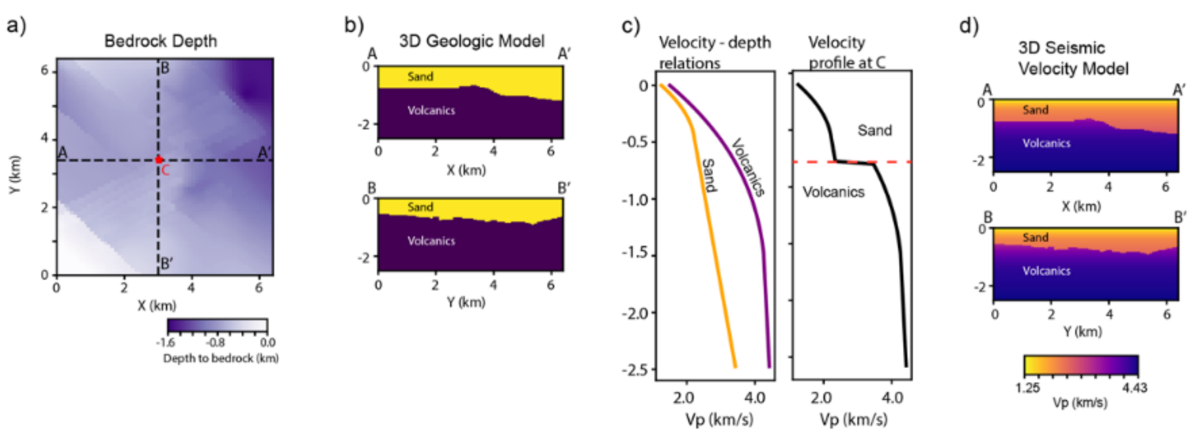


Figure 9. Construction of the 3D seismic velocity model for the DAC site. (a) 3D surface representing the top of bedrock, derived from geologic data provided by DAC operator Ormat. (b) Discretized 3D model domain where all grid points above the bedrock interface are assigned to be “sand”, while below the interface the type label is “volcanics”. (c) Velocity – depth relations appropriate for these two rock types (Brocher, 2005) are applied to the corresponding sand or volcanic units. (d) Resulting velocity profile that is continuously increasing but has a sharp increase in velocities at the bedrock interface.

3.3 Simulated motions at DAC

We tested the previously described seismic source in SW4 wave propagation simulations at DAC. The computational domain is 6.4 x 6.4 km horizontally and 2.5 km in depth; the numerical grid spacing is 5 m, which is finer than the velocity model spacing to capture higher frequency motion. We modeled the point source as a 90-degree dipping strike-slip fault at the location and depth of one of the injection wells. Slip is entirely along strike, with no vertical offset. Figure 10a shows a map of the modeled PGV at the surface. The aspects of the four-quadrant radiation pattern (like in Figure 8d) are retained but the shapes of the lobes are warped in some quadrants. PGV is also much higher to the west than to the east, which corresponds with the location of shallower bedrock (Figure 10a). It is likely that the ground motions experienced to the west of the source are amplified relative to the east, because the sharp impedance contrast at the bedrock interface is closer to the free surface. Complexity related to the geologic structure is also seen in ground motion time-histories at an example array of stations (Figure 10b). Here, reverberant motions between seismic phases as well as late reflections are present while they are absent in much simpler cases such as that shown in Figure 8c. These simulation results highlight the advantage of numerical simulations in reproducing complex seismic wavefields in complex geologic media, which are difficult to capture with empirical or analytical models.

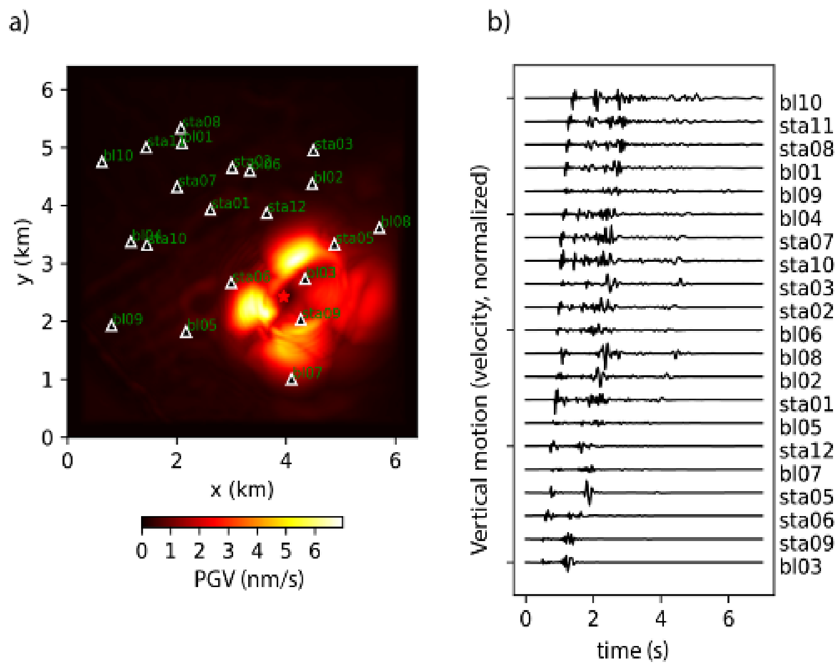


Figure 10. a) Peak ground velocity (PGV) map from a simulation at the Don A. Campbell site. b) Motions at an example array of stations distributed throughout the study area.

4. Seismic array design

Various models exist for seismic source resolution based on simple sources and geologic structure (i.e., velocity, density and attenuation models) that provide a good first estimate on the theoretical detection limits of seismic sources (e.g., Freudenreich et al., 2012). However, owing to the complex geological settings where many geothermal resources are located, simple models may not adequately capture small magnitude seismicity crucial to the success of monitoring and accurately locating reservoir stimulation. More sophisticated models are needed to provide a more in-depth look at the added complications for sensing small magnitude seismicity in geothermal settings. Based on our results we suggest the following steps to establish optimal seismic source resolution and network design:

1. Gather geologic model information including seismic velocity models (and/or sonic logs) when available, density profiles from well logs if available, and estimate attenuation structure based on rock type and alluvial cover thickness.

2. Deploy surface seismometers to gather local noise characteristics and identify locations with lower attenuation or lack of alluvial cover.

3. Conduct full waveform modeling given the geologic information and likely source depths of events induced during stimulation for a suite of source characteristics and station locations and depths.

4. Generate synthetic time series based on the Probabilistic Power Spectral Densities of the observed noise.

5. Convolve synthetic noise time series with various synthetic time series derived from full waveform modeling.

6. Identify station configurations and station depths that yield sufficient source sensitivity for the specific site.

This general protocol ensures that complex local conditions are considered and state-of-the-art modeling tools permit a very detailed look at potential seismic source sensitivity for a given station configuration.

The protocol and methods do have some caveats in that model setup and development is a time-consuming task, model execution requires high performance computing resources, and the source and model parameter exploration are somewhat limited given the wealth of geologic information, source locations and parameters, and number of station configurations. As such, this protocol is envisioned as a high-resolution end member of possible seismic sensitivity estimation. These methods outlined here also lend themselves to guide and verify simpler, more computationally efficient methods that can be optimized to generate ideal station configurations.

5. Drilling and Monitoring

Key parameters to be assessed for optimized seismic array configurations include factors such as stimulation depth, local terrain, lease boundaries, near-surface sediment thickness, expected subsurface temperatures at monitoring depths, ambient noise sources, road access, environmental footprint, natural seismicity, attenuation results from source modeling, azimuthal raypath coverage, and sufficient source sensitivity of the instrumentation balanced with overall cost effectiveness of the drilling.

The first planned stimulation site DAC is located in Mineral County, NV, on land leased from the Bureau of Land Management (BLM) by site operator Ormat. The underlying formation consists of thick poorly consolidated basin fill and the local water table is anticipated to be approximately 50 meters below ground level. Preliminary analysis of the subsurface records within a 2 km radius of the stimulation well indicates possible subsurface temperatures of 100°C or more at 100 m depth.

5.1 DAC Borehole locations

While DAC has reasonable road access and flat terrain surrounding the stimulation well for accommodating small drill rigs and field vehicles, there is an area of dunes to the north of the stimulation well that is off-limits for field deployments and the southeast quadrant is confined by the lease boundary (Figure 11). These factors have an overall effect of reducing azimuthal coverage in two quadrants by a cumulative 90-100 radial degrees. Lack of exposed hard rock within the 2 km radius and a thick underlying sediment layer means seismic signal will likely be attenuated, and the expected high temperatures at shallow depths will require more robust (but less sensitive) sensors that can survive and perform over a period of several years at 100°C or higher. We have adjusted for these limitations by adding additional monitoring wells to improve ray coverage, and reducing the completion depths to 100 m to reduce borehole temperatures and drilling completion costs. Modeling of this configuration suggests that the deployed array should be sensitive to seismic magnitudes of M < -1.5 for any local events.

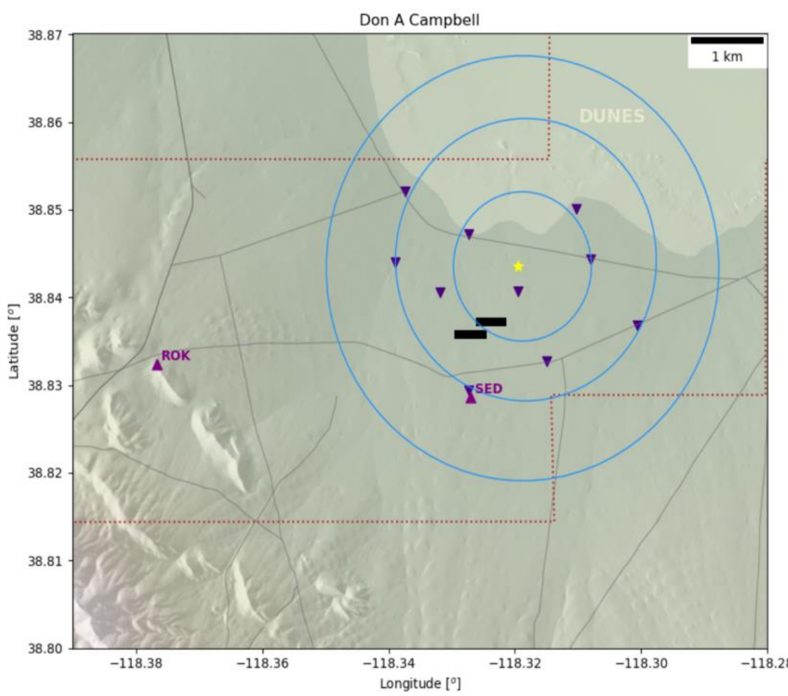


Figure 11. Map of the potential array geometry at DAC. Existing stations are labeled ROK and SED, while proposed borehole locations are shown as dark blue inverted triangles. Blue circles show the radius from the injection well location (yellow star) corresponding to 1, 1.5, and 2x the injection depth (used as an aid for station placement when considering locating events with good depth control). Dunes are light green on the north side. Stations must be within the red dotted lease boundary. Thick Quaternary sediments overlay Tertiary volcanics across the field with temperatures of 100°C expected at 100 m depth.

5.2 Permitting and Drilling plan

Due to the higher temperatures expected near the surface at DAC, the monitoring boreholes are being proposed with steel casing emplaced. AMT is working with Ormat to acquire the proper permitting per the Nevada Division of Minerals requirements. The primary drilling method will be air rotary drilling. Mud will be used when necessary. If water is necessary for drilling, the drilling fluid will be based on reclaimed brine available in abundance from DAC onsite operations.

The remaining four Amplify sites (TM, JV, PAT and COSO) have much lower temperatures at planned monitoring depths and include both hard rock and sediment drill sites, which allows for improved monitoring sensitivity as compared to DAC. However, they have other challenges such as physical access and lease boundary limitations that will play a role in the final decisions for borehole locations and depths. At sites TM and JV, the AMT plans to expand the basic drilling and completion effort to include research and development into ways to improve the economics of the process. This may include using optimization routines to select borehole locations as well as alternative drilling and installation techniques. At site PAT, a small, older borehole array already exists but is not targeted on the stimulation well location. Additional boreholes may therefore be needed to complete the monitoring array. The COSO site has a long-standing seismic array currently recording; AMT will incorporate existing data and previous subsurface studies in developing a targeted monitoring system for the selected stimulation well.

6. Conclusion

The objective of the Amplify Monitoring project is to provide near-field seismic monitoring array designs, sensor deployments, and seismic data acquisition and analysis for EGS Operators stimulating wells under the WOO-Amplify initiative. Advanced modeling, simulations and template matching techniques applied during pre-stimulation can help improve understanding of potential seismic hazard and inform each Operator's ISMP. We are currently in Phase 1 (pre-stimulation) for all five WOO-Amplify sites, working on cost-effective standardized methodologies for subsurface monitoring arrays and configuring array locations and depths to yield sufficient source sensitivity.

Our preparations for the array installation at site DAC are ongoing and we are continuing our background seismic data acquisition and modeling for DAC, TM, JV and PAT. We have started construction of our publicly accessible Amplify Monitoring website for streaming realtime seismic data from the field sites. The stimulation target for the COSO site is currently under review between the EGS Operator team and GTO. While drilling and completion of the new monitoring boreholes is dependent on stimulation schedules, we expect to have our seismic monitoring arrays installed and streaming data to our Amplify website three to six months prior to the initiation of stimulation for each site. Stimulation at the first WOO-Amplify site DAC is currently targeted for early 2023.

During stimulation in Phase 2 the AMT team will provide realtime seismic data and analyses based on optimal network configurations at the five WOO-Amplify sites. Monitoring and data streaming post-stimulation will continue in Phase 3, until completion of the WOO-Amplify Operator's project timeline for each site. These dedicated networks will provide crucial information for stimulation operations and seismic hazard estimation during stimulation, and will thus aid in maximizing the understanding of safe resource expansion. The pre-stimulation modeling and monitoring will be verified with data from the stimulation which will permit further improvements in future monitoring developments with the aim of lowering cost for geothermal operators and providing field-verified guidelines for monitoring network planning.

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