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Amplify EGS Project: Seismic Monitoring for In-field and Near-field Enhanced Geothermal Systems Stimulation at Wells of Opportunity (WOO) Sites in Nevada

Jiann Su[1], Chet Hopp[2], Michelle Robertson[2], Paul C. Schwering[1], Nori Nakata[2],
and The Amplify Monitoring Team*

[1]Sandia National Laboratories, Albuquerque, New Mexico, USA

[2]Lawrence Berkeley National Laboratory, Berkeley, California, USA

jsu@sandia.gov

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ABSTRACT

The U.S. Department of Energy's Geothermal Technologies Office assembled the Amplify Monitoring Team (AMT) to provide in-field and near-field seismic monitoring and data analysis for geothermal stimulations under the Wells of Opportunity Amplify initiative. Amplify Monitoring is a collaborative team of scientists and engineers from Lawrence Berkeley National Laboratory, Sandia National Laboratories, and the U.S. Geological Survey working directly with enhanced geothermal systems operators in Nevada in developing optimized seismic monitoring systems at four geothermal fields where well stimulations are planned. These fields include Don A. Campbell, Tungsten Mountain and Jersey Valley operated by Ormat Technologies, and Patua operated by Cyrq Patua Acquisition Company LLC. During the pre-stimulation phase, AMT's site characterizations, source simulations and 3D modeling will help improve understanding of potential seismic hazard at each site and inform the Operator's Induced Seismicity Mitigation Protocol. During the stimulation phase, AMT will provide real-time seismic information to operators including locations and magnitudes, and will continue long-term seismic monitoring operations during the post-stimulation phase at each site. Over the next two years, AMT will be installing borehole seismic monitoring systems at all four WOO-Amplify field sites, telemetering the waveform data to AMT's central processing system and providing the processed location data in real-time to the operator teams. These data, models, telemetry systems, and lessons-learned will be critical for effective monitoring of the effects of planned well stimulations and extended flow tests, with the seismic data available to commercial operators and the public.

1 INTRODUCTION

DOE's Geothermal Technologies Office (GTO) launched the Wells of Opportunity (WOO) Amplify initiative in late 2020 with the focus of improving the performance of underproductive and/or low-permeability commercial geothermal wells for increased power production. This initiative has the added benefit of providing testbeds for in-field and near-field EGS (unproductive wells within conventional hydrothermal fields, and hot impermeable rocks just outside of a conventional system, respectively), thus helping with DOE's stated goal of dramatically increasing power production from EGS resources (DOE, 2019). The four current WOO-Amplify geothermal sites are all located in the Basin and Range province of western Nevada (Figure 1.): Don A Campbell, Tungsten Mountain and Jersey Valley operated by Ormat Technologies, and the Patua field operated by Cyrq Patua Acquisition Company LLC.

In partnership with WOO-Amplify, GTO also initiated the Amplify EGS Monitoring and Characterization project, or Amplify Monitoring, with the focus of providing the seismic monitoring data most needed by EGS operators for successful commercial reservoir stimulation. The Amplify Monitoring Team (AMT) consists of scientists and engineers from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL) and the U.S. Geological Survey (USGS).

Amplify Monitoring has three project phases (Figure 2). Pre-stimulation Phase 1 focuses on site characterization, baseline seismic data acquisition, noise analysis, velocity model development, monitoring array design and sensor installations, and real-time waveform data streaming to our Amplify Monitoring website. Simulation and modeling results are shared and discussed with the individual operators to assist them with their Induced Seismicity Mitigation Plan (ISMP) development. During Stimulation Phase 2, AMT monitoring at the stimulation site will be augmented with real-time waveform streaming to operator-specific interfaces including automated seismic locations and magnitudes with the option of expanding the monitoring array with temporary high-resolution sensor deployments (e.g., surface nodals or multi-level borehole arrays). Seismic monitoring will continue during post-stimulation Phase 3, including waveform streaming and seismic data analyses available through the Amplify website. Data from each of these phases will be available to update EGS Best Practices protocols (e.g., Majer et al., 2012), and update operator 3D subsurface models. The Amplify Monitoring project is currently in Phase 1 while the WOO-Amplify operators prepare their stimulation plans.

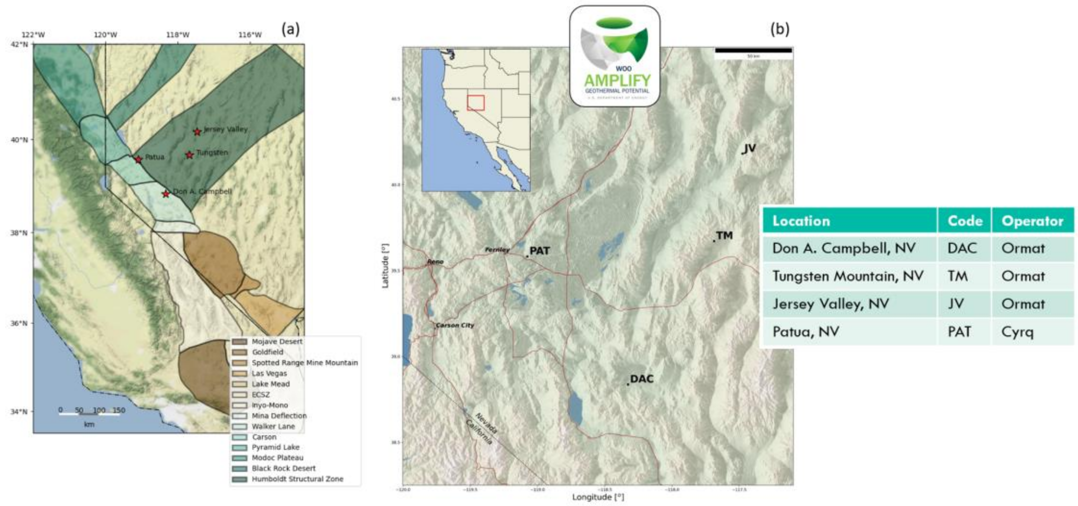

Figure 1. Location of the four Wells of Opportunity (WOO) Amplify geothermal sites to be seismically monitored by AMT. (a) Jersey Valley (JV), Tungsten Mountain (TM) and Patua (PAT) fall within the Humboldt Structural Zone, and the fourth site Don A. Campbell (DAC) is within the adjacent Walker Lane region (graphics modified from Faulds et al., 2008). (b) Topographical view of the four WOO-Amplify sites.

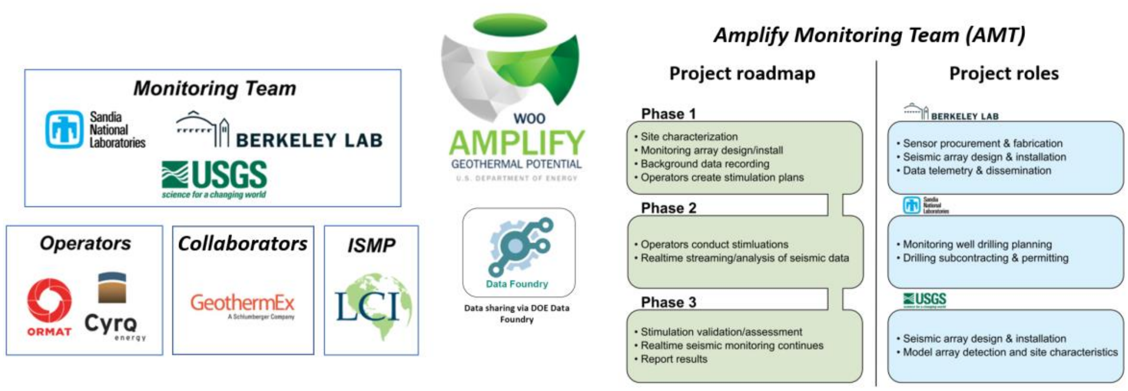

Figure 1. Collaborative teams, project roadmap and roles for the Amplify Monitoring project.

2 SITE CHARACTERIZATION

In preparation for designing the borehole seismic monitoring networks for the four WOO-Amplify geothermal sites, AMT expanded the existing public regional seismic catalogs to improve our understanding of the occurrence of seismicity and the observable range of event magnitudes in each area. We also performed onsite seismic noise analyses to estimate the detection capabilities of borehole seismic sensors for the smaller magnitude events.

2.1 Expanding Seismic Catalogs using Regional Seismicity

A commonly used technique in seismic processing applies template matching algorithms to seismic data collected in various geologic settings, especially in areas of low natural seismicity, to expand existing seismicity catalogs and further understand the extent and timing of microseismic events. Template matching or matched filter techniques aim to extend known seismic catalogs by convolving seismic recordings from known earthquakes with continuous seismic records and finding previously undetected smaller seismic events (e.g., Skoumal et al., 2019). The resulting expanded catalogs provide more complete seismic background information for each site to help the operator improve their ISMP and to possibly identify structure within the geothermal reservoirs to aid understanding of possible seismic sources.

Using publicly available seismic data archived at the Incorporated Research Institutions for Seismology (IRIS), we processed continuous waveform data using the template matching approach. In the example below, we generated templates of P wave arrivals using a Mw 2.9 event that occurred on May 15, 2020, near the PAT site. Stations KVN, LHV, BRH5 and CMK6 in the Nevada Seismic Network showed clear arrivals and high signal to noise ratios. We calculated the Median Absolute Deviation (MAD), which is a function of a minimum threshold (10) multiplied by the median absolute value of the cross-correlation sum between the templates and the filtered continuous waveforms (e.g., Schaff and Richards, 2014). We then used the python software package EQcorrscan (Chamberlain et al., 2018) to compile a list of detections for each station and we visually inspected the possible detections to confirm they were seismic events. The cumulative detection count for each station is shown in Figure 3.

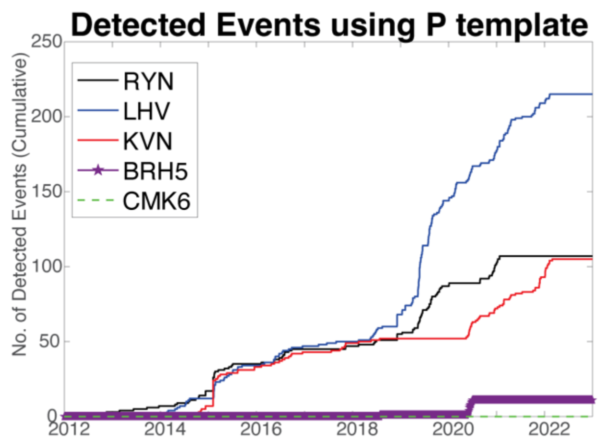

Figure 2. Events are detected by implementing the EQcorrscan python package (Chamberlain et al., 2018) using templates made from P waves (figure from Marusiak et al., 2022). Using data from station LHV we found the most events, followed by data from stations RYN, and KVN. Stations BRH5 and CMK6 only came online in 2019 and thus had the fewest detections.

2.2 Noise Analysis using Surface 3C sensors

Characterizing noise at the surface and within the subsurface helps guide seismic network planning immensely in two ways: surface noise sources (i.e., geothermal plant, highways) can be identified and quantified in advance and their impacts mitigated by moving monitoring stations or deepening boreholes, and intrinsic attenuation of near-surface material can be quantified relative to hard-rock stations or deeper borehole stations. Intrinsic attenuation near the surface can be very large, especially in unconsolidated alluvium commonly found in the valleys at Basin and Range sites in Nevada. The unconsolidated valley fill subdues the eventual seismic signals at stations located within it and significantly reduces the sensitivity of the seismic monitoring network. We therefore try to understand the local conditions near the surface prior to network planning.

At each of the Ormat sites DAC, TM, and JV we installed two 3C surface monitoring stations: one on hard rock (ROK) and one on basin sediment fill (SED). The Patua site had the benefit of five existing borehole 3C geophones that were still functional from a Leidos array operating from 2012 to 2014; we added surface 3C geophones at each borehole and recorded six channels at each location for PAT. Results of the noise analyses from these sites showed that the ROK stations had 20-30 dB lower noise as compared to the SED surface stations for frequencies higher than 1 Hz at DAC, TM and JV, with significant noise noted at borehole stations near the DAC and PAT plants. These noise results were incorporated into our seismic network planning to improve seismic signal sensitivity for the upcoming borehole drilling and borehole seismic sensor installations.

3 MODELING AND SIMULATIONS

Where available, well logs and initial reservoir models provided by the WOO geothermal operators are included in our constructions of 3D velocity, density, and attenuation models for each of the field sites. When local measurements are not available, physical properties are distributed throughout our 3D models using literature values for comparable geologic settings. Once the models are compiled, we place various simulated seismic sources (e.g., strike-slip, normal-fault earthquakes) at and near the stimulation depths and perform full waveform modeling to calculate particle velocities at the proposed seismic stations. The calculated surface and borehole velocities at the stations are then convolved with random time series of observed noise at each site to establish lower sensitivity bounds for various network designs. We are currently iterating through a suite of models and seismic sources to yield more comprehensive lower sensitivity bounds for various sensor depths at each site.

3.1 Velocity model

To model geologic structure and subsurface seismic velocities at DAC, we started with a 3D interface representing depth to bedrock in Figure 4a derived from proprietary well logs shared by Ormat as well as geologic information presented by Delwiche (2013), Orenstein and Delwiche (2014), and Winn et al. (2021). Using this 3D surface, we constructed a simple two-layered velocity model (Figure 4b) where lower velocity Quaternary sand-rich sediments overlie higher velocity volcanic bedrock. We then discretized the 3D model using a grid with 25 m spacing from ground surface to 2.5 km depth and assigned material properties and associated Vp velocities to each grid point using relations from Brocher (2005) shown in Figure 4c. Our resulting 3D seismic velocity model in Figure 4d shows increasing velocity with depth with a distinct increase in velocity at the sand-bedrock interface surface.

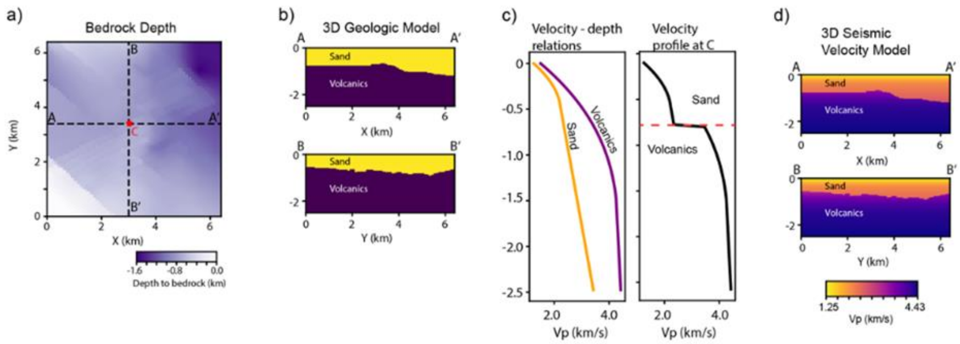

Figure 4. Development of a three-dimensional velocity model for the Don A. Campbell site in Nevada operated by Ormat (figure from Robertson et al., 2022). Starting with the 3D surface in (a) derived from geologic well logs denoting top of bedrock provided by Ormat, we constructed a discretized 3D model domain in (b) where all grid points above the bedrock interface are assigned to be "sand" and below the interface are "volcanics." Applying the velocity-depth relations shown in (c) for sand and volcanic rock units (Brocher, 2005), our resulting velocity profile (d) shows continuously increasing velocity with depth with a sharp increase in velocities at the bedrock interface.

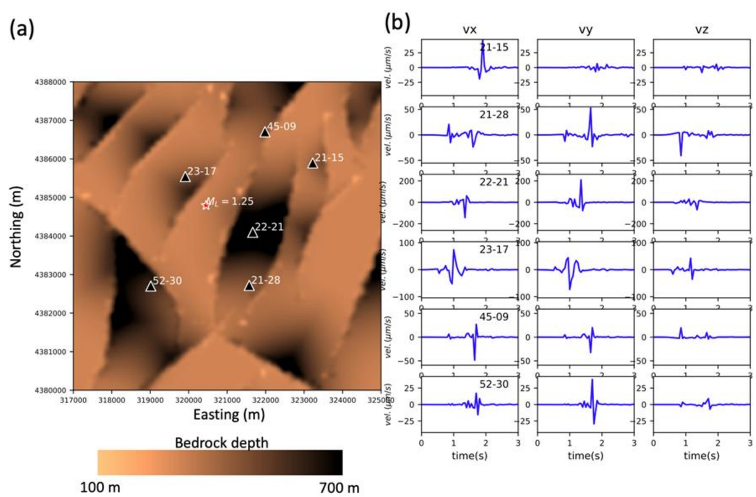

Figure 5. (a) Simulation domain, station locations (black triangles), and epicenter location (red star), for a simulated M1.25 earthquake recorded at the Patua site. The colormap shows depth to bedrock. The earthquake is modeled as a point source at the hypocentral location, with a normal fault focal mechanism consistent with local fault strike and dip. (b) Synthetic seismograms (velocity time series, in micrometers/second) computed at Patua stations. Peak ground motions are higher at stations above deep basement (e.g., ~200 micrometers/second at 22-21) than other stations that are equidistant from the source but are above a shallower sediment layer (e.g., less than 100 micrometers/second at 23-17).

3.2 Simulated Motions

For the Patua geothermal site, we developed the 3D seismic velocity model by creating a stratigraphy model based on inferred geologic surfaces (Pollack et al., 2020) and assigning seismic properties to each layer based on rock-type-specific velocity-depth relations (Brocher, 2008). The resulting model has low velocity sediments at the surface with variable depth to bedrock (Figure 5a). We then applied this model in seismic wave propagation simulations using SW4, a 4^{th} order accurate finite-difference code (Petersson and Sjogreen, 2017), and simulated motions from a virtual M_L 1.25 event with a hypocenter located directly under PAT. Simulated ground motions are noticeably higher at stations where bedrock depth is deep, indicating a strong basin-like response (Figure 5b). The next step will be to compare these simulated motions with actual motions from recorded events in the seismic catalog, to evaluate the accuracy of the velocity model. Computer simulations of seismic wave propagation in the vicinity of EGS sites allow for better understanding of seismic motions associated with geothermal activities and inform the operator's ISMP.

4 DRILLING AND PERMITTING AT DAC

The first WOO-Amplify site in the planned stimulation schedule is Ormat's DAC site located in Mineral County, Nevada, on land leased from the Bureau of Land Management (BLM). Based on proprietary well log information and an initial 3D geologic model shared with AMT by Ormat, we are expecting thick unconsolidated basin fill within a 2 km radius of the proposed stimulation well, a local water table depth of approximately 50 m, and subsurface temperatures of 100°C or more at 100 m depth. In contrast, the other two Ormat sites JV and TM have much lower subsurface temperatures (~70°C) at the planned monitoring depths and include both thick sediments and hard rock drilling locations that would allow for improved monitoring sensitivity.

Elevated temperatures at monitoring depths compel the use of steel casing that requires specific permitting in Nevada. A schematic of the borehole completion for the planned monitoring array for DAC is shown in Figure 6a. Three-component borehole sensor sondes have been designed and built at LBNL's Geosciences Measurement Facility (gmf.lbl.gov) using commercial high-temperature (up to 200°C) omni-directional 15 Hz geophone elements, with two sensor elements per component to boost sensitivity (Figure 6c). These sondes will be sanded in at the bottom of each steel-cased borehole for improved coupling to the casing and host rock, with high-temperature wireline cable to the surface. Seismic recorders at the surface of each borehole will telemeter the data via cell modem to the Amplify central processing system in real-time. A total of nine boreholes are to be installed at varying radial distances from the proposed stimulation well at DAC, with the dual requirement of being located within Ormat's lease boundary and avoiding the restricted dunes area to the northeast (Figure 6d).

DAC has good road access for field vehicles and small drill rigs with mostly flat terrain within two kilometers of the proposed stimulation well. However, the constraints of Ormat's lease boundary and the restricted dunes area reduce the azimuthal coverage of the seismic monitoring array by ~90-100 radial degrees at the furthest radial offsets. In addition, there are no hard rock exposures within a 2 km radius from the stimulation well and the thick valley sediments will likely attenuate seismic signals in the subsurface. The expected temperatures at shallow depths necessitate sensor sondes that are capable of performing for several years at 100ºC or higher, as well as a commercial crew and equipment prepared for drilling at higher temperatures. To offset these limitations at DAC, we increased the number of borehole stations to improve ray coverage, and will continue to operate the long-offset ROK site to augment the seismic monitoring array. Initial seismic source models using this array configuration show a magnitude sensitivity of M < -1.5 for local microearthquake events.

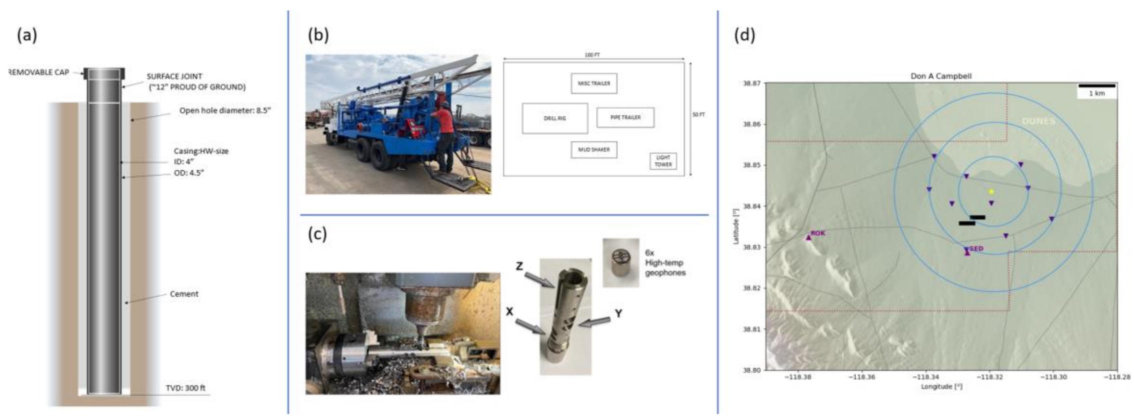

Figure 6. Monitoring site preparations for DAC, including (a) the DAC monitoring well schematic, (b) the SpeedStar 15 drill rig and surface foot print, (c) 3C sensor sonde manufacturing at LBNL, and (d) a topographic map of planned DAC borehole locations (inverted triangles) and the location of the current ROK and SED surface monitoring locations (purple triangles). Ormat's lease boundary is marked by the red dotted lines and there is an area of dunes shaded in light green to the north of the proposed monitoring array that is off limits.

4.1 Drilling Plan

The primary drilling method for the Amplify Monitoring boreholes will be air rotary drilling with mud used when necessary. For water conservation the drilling fluid will be based on reclaimed brine available from onsite commercial operations. For DAC, the team has contracted with a Nevada-based driller that will use a Speed Star 15 SS to drill and complete the boreholes. The rig and estimated surface disturbance area are shown in Figure 6b. The rig details include an 8-inch rotary table, duplex pump, air compressor, mud shaker unit and 3.5-inch drill pipe; completion will be 4-inch steel casing to the surface.

4.2 Permitting

AMT is working with Ormat to acquire the proper permitting per the Nevada BLM requirements for sites DAC, TM, and JV. A permit to drill at DAC was granted in October 2022. However, there are conditions of approval (COA) associated with the permit that have to be met prior to the start of drilling. The conditions of approval fall into two primary categories: Drilling Operations, and Surface and Environmental. Each type of condition is described in additional detail in the sections below.

4.2.1 Conditions of Approval (Drilling Operations)

Conditions of approval for the drilling operations are straight-forward and are not expected to have a significant impact on planning and execution of the drilling plans. The driller has prior experience in following the drilling COA's. The COA's for drilling are listed below.

1. If Hydrogen Sulfide is encountered well must be shut-in until measured amounts are determined, and these must be reported to the BLM.
2. For Air/Aerated drilling operations, the following equipment shall be utilized: banjo box (or equivalent); a staked down blooie line directed to a blooie pit a minimum of 100 ft. downwind of the wellhead.
3. Daily drilling and completion progress reports shall be submitted to the Bureau of Land Management daily and shall include both daily mud reports and directional survey data.
4. If prior approval has not been granted for well testing, a Sundry Notice prior to commencing any testing must be submitted and approved.

The AMT drilling management team will work with the driller to ensure that these COA's are met during drilling and completion activities.

4.2.2 Conditions of Approval (Surface and Environmental)

According to the permit COA, previous baseline surveys for the DAC environmental assessment in 2012 (DOI 2012) were not conducted during the proper floristic timeframes and did not include surveys for updated special status species plants. As a result, surveys must be completed prior to drilling and/or surface disturbance of the proposed areas. Sensitive plant species that have the potential to occur in the project area are to be monitored for in their respective ideal floristic timeframes. For annual species, if surface disturbance activities occur during their specific growing season timeframe, botany surveys are to be conducted in the specified project area by qualified, BLM-approved biologists not more than 7 days prior to surface disturbing activities commencing. For perennial species, botany surveys are to be conducted in the specified project area by qualified, BLM-approved biologists not more than 7 days prior to surface disturbing activities commencing regardless of seasonality.

Additionally, due to the migratory bird nesting season from March 1st to August 31st, annually, if surface disturbing activities must occur during this period, pre-construction avian surveys are to be conducted in appropriate habitats by qualified, BLM-approved biologists not more than 7 days prior to surface disturbing activities commencing.

A list of the floristic timeframes for the species expected in the area are provided in Table 1. The consequence of the COA is that the timeframe in which drilling can occur is tightly constrained based on the botanical survey periods. The Amplify team can drill and complete three wells without additional surveys (DAC03, DAC06, DAC08), given that they are sited in previously disturbed ground. However, the other wells will not be drillable until at least May 2023, due to the pre-construction survey requirements.

Table 1. DAC plant species and floristic timeframes

Species	Annual/Perennial	Flowering Timeframe	Preferred Habitat	Potential to occur based on NRCS mapped soil types and SWReGAP mapped landcover types (y/n)								
				DAC01	DAC02	DAC03	DAC04	DAC05	DAC06	DAC07	DAC08	DAC09
Astragalus lentiginosus var. sesquimetralis (Sodaville milkvetch)	Perennial	May - June	This species is restricted to powdery clay saline soils, adjacent to springs and moist alkaline flats. Near exhaustive surveys of habitat have revealed only two populations in Nevada; one in Sodaville, Mineral County and the other in Cold Springs, Nye County (NatureServe Explorer 2022a; Schweich 2022).	Survey	Survey	N/A - existing disturbance	Survey	Survey	N/A - existing disturbance	Survey	N/A - existing disturbance	Survey
Oryctes nevadensis (oryctes)	Annual	April - June	Occurs in deep loose sand of stabilized dunes, washes, and valley flats, on various slopes and aspects (NDNH 2022).	Survey	Survey	N/A - existing disturbance	Survey	Survey	N/A - existing disturbance	Survey	N/A - existing disturbance	Survey
Oxytheca watsonii (Watson's spine cup)	Annual	May - July	Occurs in dry, open, loose and/or lightly disturbed, often calcareous, sandy soils of washes, roadsides, alluvial fans, and valley bottoms, in salt desert shrub communities (NDNH 2022).	Survey	Survey	N/A - existing disturbance	Survey	Survey	N/A - existing disturbance	Survey	N/A - existing disturbance	Survey
Penstemon palmeri var macaranthus (Lahontan beardtongue)	Perennial	May - July/August	Occurs along washes, roadsides, and canyon floors, particularly on carbonate-containing substrates, usually where subsurface moisture is available throughout most of the summer; unknown if restricted to calcareous substrates (NDNH 2022).	Survey	Survey	N/A - existing disturbance	Survey	Survey	N/A - existing disturbance	Survey	N/A - existing disturbance	Survey
Penstemon arenarius (Nevada dune beardtoungue)	Perennial	May - July	Occurs in deep loose sandy soils of valley bottoms aeolian deposits, and dune skirts, often in alkaline areas sometimes on road banks and other recovering disturbances crossing such soils (NDNH 2022).	Survey	Survey	N/A - existing disturbance	Survey	Survey	N/A - existing disturbance	Survey	N/A - existing disturbance	Survey

5 CONCLUSION

Under the WOO-Amplify initiative and in collaboration with the WOO commercial operators, the Amplify Monitoring project team is providing seismic monitoring array designs, modeling and simulations, subsurface sensor deployments, and real-time transmission and processing of seismic data to EGS operators stimulating in-field and/or near-field geothermal wells in Nevada to increase production. We are currently in pre-stimulation Phase 1 for all four WOO-Amplify sites in Nevada and we are in the monitoring array preparation stage for Ormat's DAC site currently targeted for stimulation in the second half of 2023. Background noise and baseline seismic data recorded in the months prior to stimulation as well as noise analysis and template matching techniques applied during pre-stimulation can help identify potential seismic hazard and inform each operator's ISMP. Template matching techniques are becoming more accessible to users that need not be an expert seismologist. All recorded seismic data including the continuous waveforms from each station will be available to each operator and will eventually be shared to the public via the IRIS data center. The full waveform modeling prior to stimulation, and the comparison with resultant microseismicity during and after stimulation, will help guide best practices for EGS monitoring. While full waveform modeling is unlikely to be carried out by individual operators for their future monitoring network designs, our detailed analyses and comparisons to observed seismicity will yield generally applicable guidelines for seismic network designs that can directly benefit operators. This seismic monitoring approach is designed so that it can be adopted by commercial operators planning to conduct EGS stimulation activities as part of future geothermal field operations.

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