PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Seismic Monitoring at the Utah Frontier Observatory for Research in Geothermal Energy

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Keywords: FORGE, micro seismicity, EGS, geophysics

ABSTRACT

Seismic monitoring at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is required for: (1) seismic hazard and risk assessment and mitigation; and (2) monitoring of fracture growth and reservoir development. Using the University of Utah regional earthquake catalog combined with more detailed seismic analyses compiled as part of the FORGE project, seismicity in the region can be characterized by low rates and low magnitudes. There is a region of small magnitude (M less than 2.5) natural tectonic activity and possibly seismicity related to injection at the Roosevelt Hot Springs geothermal system to the east of the FORGE site and a tectonic source zone to the south of the FORGE site near the town of Milford, Utah. Pre-development seismic monitoring has found that the immediate footprint of the FORGE facility is aseismic. To inform future seismic monitoring programs, seismic monitoring was performed during a stimulation test of well 58-32, a 2297 m vertical well, in the spring of 2019. Two boreholes were drilled to depths of ~300m and ~1000m. In the shallower hole, two sensors were tested to evaluate comparative sensitivity. These sensors were: (1) a three-component high-frequency geophone with four sensors per component; and (2) a three-component accelerograph. In the deeper well (~1,000 m TVD), stimulation was monitored with an industry-proven 12 sensor, three-component string of sondes, and a Distributed Acoustic Sensing (DAS) fiber optic cable. The seismic signals from these tests were analyzed to measure detection levels. In addition, a dense array of three-component geophones was installed on the surface to assess the detection threshold and to characterize the local velocity structure. The data collected during this experiment will be used to inform the seismic monitoring program for future drilling and the stimulation of deep, highly deviated production and injection wells. In this paper, we discuss the results of seismic monitoring at the Utah FORGE site and plans for future monitoring.

1. INTRODUCTION

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site is located 320 km south of Salt Lake City, Utah and 16 km north of Milford, Utah, a small community with a population of 1400. The FORGE site is unpopulated and covers an area of about 5 km^2. It is situated within Utah's Renewable Energy Corridor adjacent to a 306 MWe wind farm, a 240 MWe solar field and PacifiCorp Energy's 38 MWe Blundell geothermal plant at Roosevelt Hot Springs. Cyrq Energy's 10.5 MWe geothermal field at Thermo and a biogas facility currently producing 1.5 MWe are located south of Milford. An extensive road system provides access to the site.

The FORGE site, is situated on the western edge of the Intermountain Seismic Belt (ISB), a north-south trending band of earthquakes that extends from Montana into Arizona (Smith and Arabasz, 1991) (Figure 1). Analysis of the Utah historical catalog dating back to 1850 (Arabasz et al., 2015) indicates there has been only one M > 4 earthquake in the general area surrounding the Utah FORGE site. This was the 1908 M 4.1 Milford earthquake (Figure 2). Additional analysis of the historical and more modern earthquakes catalogs (Burlacu et al., 2019; Potter, 2017) indicates that within the Utah FORGE area seismicity has been clustered in the Mineral Mountains to the east of the Utah FORGE site, in a region immediately northest of the town of Milford, and to the northwest of Milford near an active quarry (Figure 2). For all of these areas, the seismicity is characterized by low magnitudes occurring at low rates (Pankow et al., 2019; Potter, 2017).

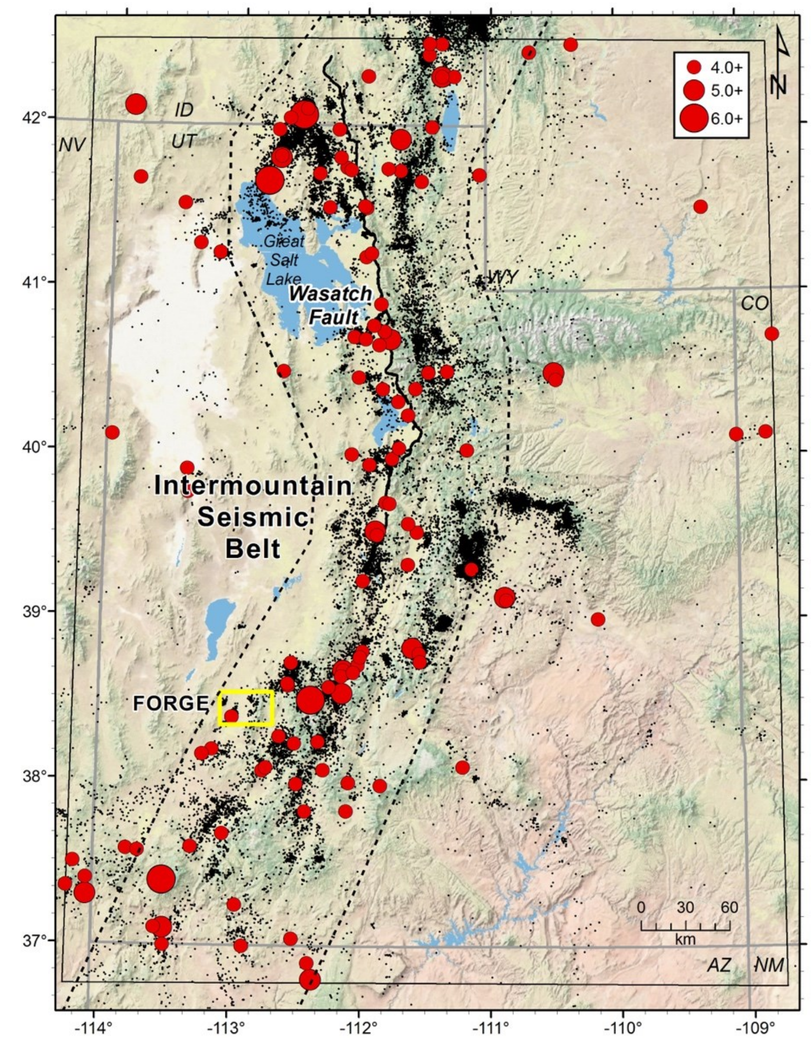

Figure 1: Location of Utah FORGE site relative to the Intermountain Seismic Belt (black dots and red circles). Red circles, M > 4 earthquakes in Utah (Arabasz et al., 2015).

In December 2016, a local FORGE seismic network consisting of five surface broadband stations was installed in the Utah FORGE area (FORU, FOR1, FOR2, FOR3, and FOR4) (Figure 2). These new stations were integrated into the Utah Regional Seismic Network (URSN). From the installation through December 2019, 234 earthquakes (M -0.87 to 1.89) have been located. Overall, the earthquakes detected and located with the local FORGE network continue to locate in the same areas detected with the regional network—under the Mineral Mountains to the east of the FORGE site and in the region northwest of the town of Milford, Utah (Figure 2).

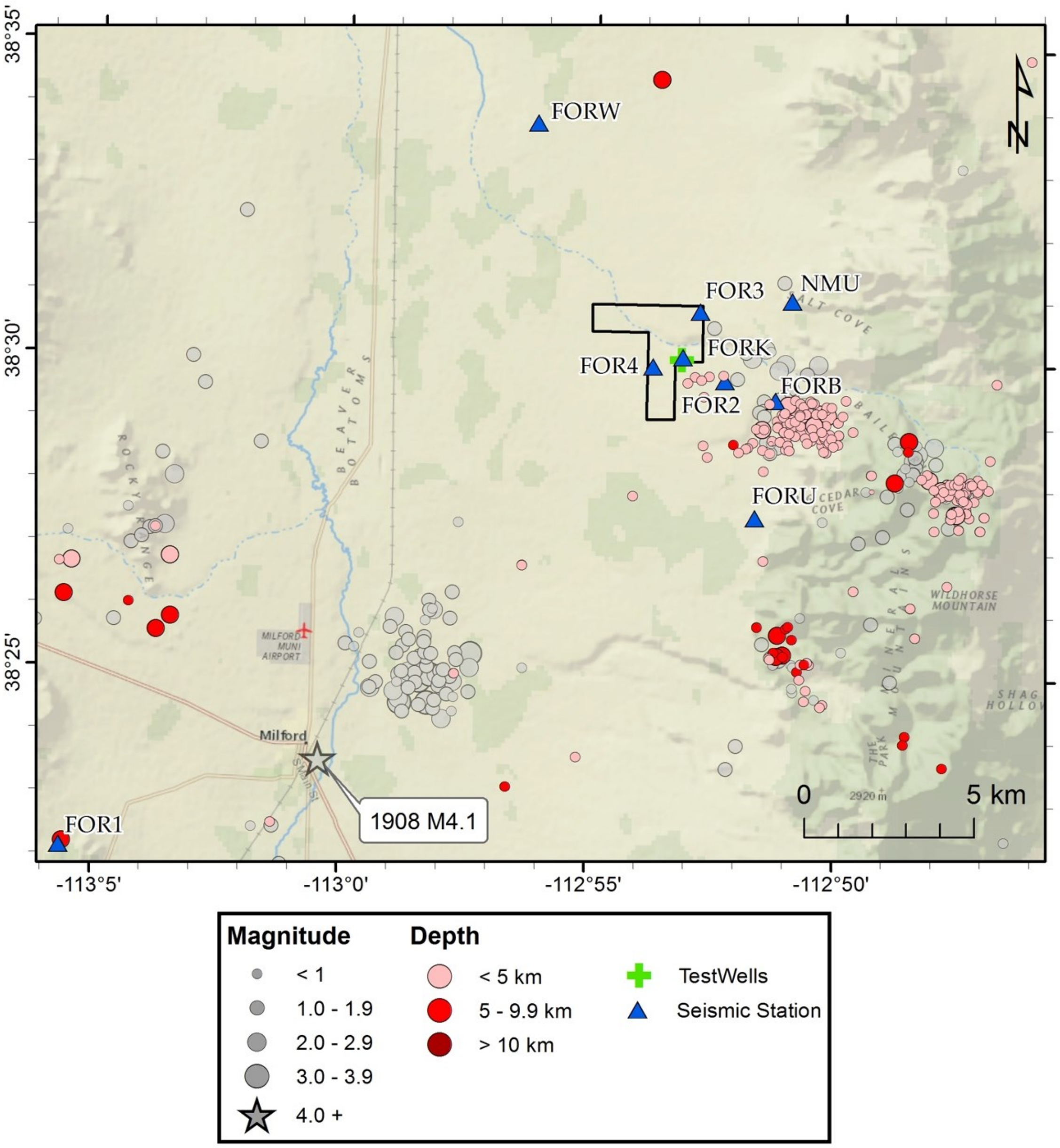

Figure 2: Map showing local seismic network (blue triangles) and seismicity in proximity of the Utah FORGE site. Seismicity shown as pink and red circles is for the time period November 2016 through December 2019 color coded by depth. Grey circles show earthquakes detected and located prior to establishing the local FORGE network. Green cross, borehole 58-32. FORK is deployed in well 68-32.

In 2019, the local FORGE network was expanded to include two boreholes (68-32 and 78-32) (Figure 3) and three surface accelerometers (FOR3, FORB, and FORW) (Figure 2). In addition to the local network, several temporary high-density geophone experiments have been carried out over the Utah FORGE region. In this paper, we focus on data collected during a low volume stimulation of well 58-32 (Figure 2 and 3) during April and May of 2019. The primary objective of the seismic monitoring was to compare detection thresholds from different types of seismic sensors (a borehole geophone string, intelligent Distributed Accoustic Sensors (iDAS), shallow borehole instruments, the local and regional surface network, and a dense surface geophone deployment). We conclude with lessons learned and implications for permanent seismic monitoring at the Utah FORGE site.

Figure 3: Photo (looking southeast) showing the relative location of the three boreholes. Well 68-32 is ~100 m northeast of 58-32 and 78-32 ~400 m southeast of 58-32.

2. SEISMIC MONITORING

Three stimulations were performed in well 58-32, which was drilled to a depth of 2297 m and temperature of 199 ^{o}C. The first stimulation was performed in the 45 m of open hole below the 9 5/8" casing shoe at the base of the well. The second and third stimulations were designed to determine the viability of stimulating fractures with different orientations behind casing. The lower perforated zone, between 2116-2129 m was located in a region of critically stressed fractures (fractures trending NNE parallel to σ_{Hmax}). The uppermost zone was perforated from 1995-1998 m. This zone contained a few fractures oriented at a high angle to σ_{Hmax} (noncritically stressed). It was assumed this zone would represent the upper limit of injection pressures required to stimulate the granite. Pressure data demonstrate the lower perforated interval and the open hole section were successfully stimulated. During the third stimulation both the packer and bridge plug failed, which limited the pressures applied at the wellhead. It is not known if fracture initiation occurred in this zone.

The primary goal of seismic monitoring during the stimulation of 58-32 (19 April through 2 May 2019) was to assess detection levels for the various seismic instrumentation deployed at the time. We break the instrumentation into three broad categories: (1) the local and regional seismic network including instrumentation in a shallow borehole; (2) instrumentation of a deep borehole using a 12-level geophone string and an iDAS; and (3) a dense array of surface geophones. The monitoring was performed by multiple groups using a variety of techniques.

2.1 Local and Regional Network and Shallow Borehole

The local FORGE seismic network is embedded into the larger URSN, and data from this network is telemetered to the University of Utah in near-real-time for processing and archiving. The network consists of five broadband stations installed as part of the FORGE project (Figure 2). Three are immediately on top of the FORGE footprint (FOR2, FOR3, and FOR4). Two stations (FOR1 and FORU) are installed on rock, a quieter environment, further from the FORGE site in order to provide some azimuthal control. In addition to the broadband stations, there are strong-motion accelerometers installed at FOR3 and near the windfarm and the geothermal power plant (FORW and FORB, respectively, Figure 2).

In addition, a shallow borehole (well 68-32) was drilled to a depth of ~300 m ~100 m to the northeast of well 58-32 in March 2019 (Figure 3). In this hole, we installed two three-component instruments that were packaged together for deployment. The station is named FORK and the sensor type named following SEED convention. The first sensor package is a three-component 0.25g Silicon Audio accelerometer (EN, later renamed GN). The advantage of this instrument is that it has a broad frequency response and high dynamic range, but is temperature limited to 80 °C. The second sensor is a three component 15-Hz geophone (EH, later renamed GH). For the geophone, each component is comprised of four OMNI-2400 sensors in order to enhance the signal. Advantages of this instrumentation include simpler electronics and the potential to be deployed in higher temperature conditions (150 °C). Disadvantages include a narrower frequency response. URSN stations that are important for monitoring seismic activity at FORGE include short-period stations NMU, IWU, and DWU and broadband station TCRU.

2.2 Deep Borehole Sensors

A second borehole (well 78-32) was drilled to a depth of ~1000 m (~200 m into the granite) ~400 m southeast of 58-32 (Figure 3). A DAS cable was encased in steel and cemented into the annulus of the 5.5 inch casing string by Silixa. In this survey, the iDAS had a gauge length of 10 m and a running average over 10 m was output every 1 m along the cable. The iDAS data was collected and processed for event detection and location by Silixa. In addition, a 12-level three-component geophone string was deployed by Schlumberger. Six of the geophones were in the granite; the remaining six in the overlying alluvium. The geophone string data was processed by Schlumberger to provide a catalog of event detection, location, and moment magnitude. Data from both the iDAS and geophone string were only collected during the stimulation of well 58-32.

2.3 Geophone Experiment

To augment the local seismic network and capitalize on enhanced detection capabilities from seismic array processing, 151 5-Hz three-component geophones were deployed in five concentric rings centered on well 58-32 (Figure 4) from 07 April to 29 April, 2019. The radii of the rings were 100 m, 223 m, 500 m, 1180 m, and 2500 m, respectively. These instruments do not allow for telemetry, so all processing occurred after the stimulation.

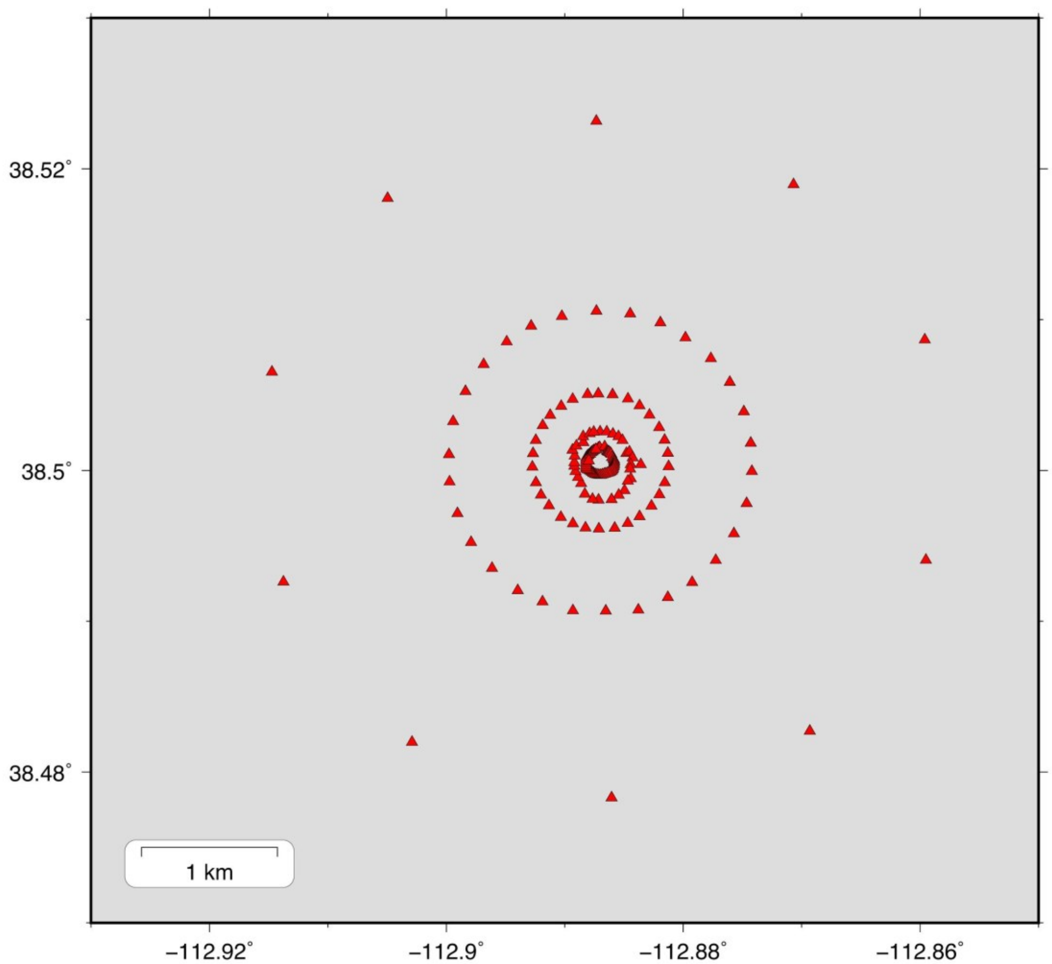

Figure 4: Spatial distribution of the geophone array.

3. SEISMIC DETECTION RESULTS

Prior to the stimulation, two check shots were set off in well 58-32 to ensure the systems were operational. All of the systems recorded the shots (M -1.17 and M -1.65). The most complete catalog of events during stimulation (435 events, M -1.996 to -0.519) was that compiled by Schlumberger using the 12-level geophone string (crosses, Figure 5). Figure 5 compares the results from the other instrumentation to this catalog. Of the Schlumberger events, Silixa detected and located 40 (blue triangles, Figure 5; Schlumberger determined magnitudes M -1.653 to -0.519). During the stimulation, twelve events were located using the local and regional seismic network, eight of which were located near the injection well (cyan diamonds, Figure 5).

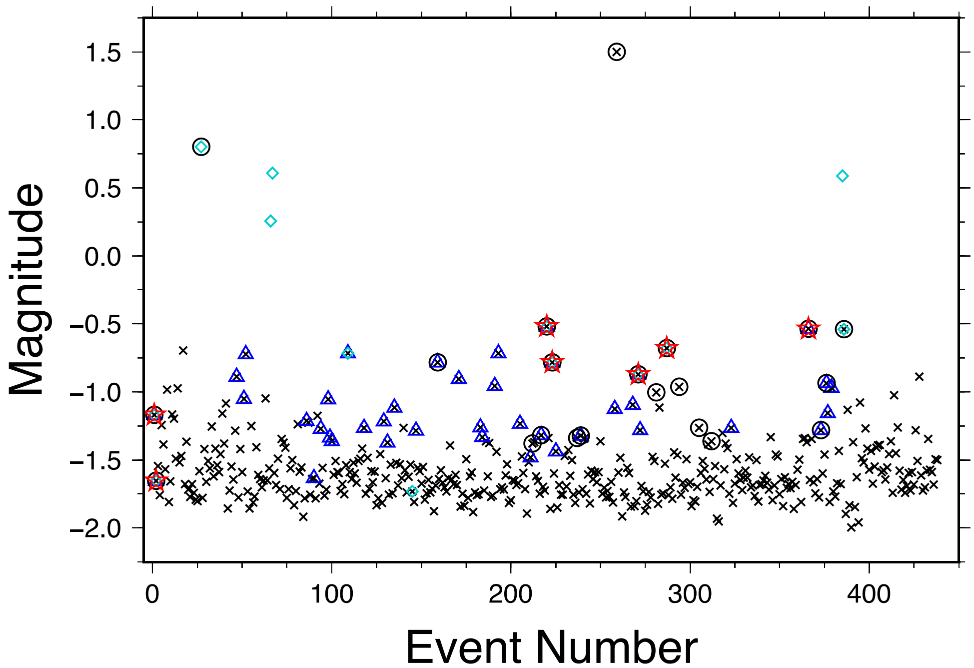

Figure 5: Detection levels from the different seismic instrumentation during the stimulation phase (19 April through 2 May 2019). Crosses, borehole geophone string (Schlumberger); Blue triangles, iDAS (Silixa); Black circles, shallow borehole; Red stars, surface geophone array; Cyan diamonds, detected and located by URSN. The first two events recorded by all were check shots. For one event a magnitude could not be determined and is assigned NaN.

Unfortunately, integration of the shallow borehole into the network processing was not successful. The shallow borehole was too close to well pad activities and the raw signal was swamped by noise. To estimate detection levels at this station, post-processing was performed to determine appropriate filters and detection levels. Optimal processing was accomplished when the data were first filtered from 30 to 300 Hz and then an STA/LTA was applied to the two horizontal components. This application produced over ~2,000 detections. These detections were manually reviewed and 19 were confirmed as real events (black circles, Figure 5 and Figure 6) including one regional event (Schlumberger determined magnitudes M -1.6 to -0.519, and M 0.803 for the regional event).

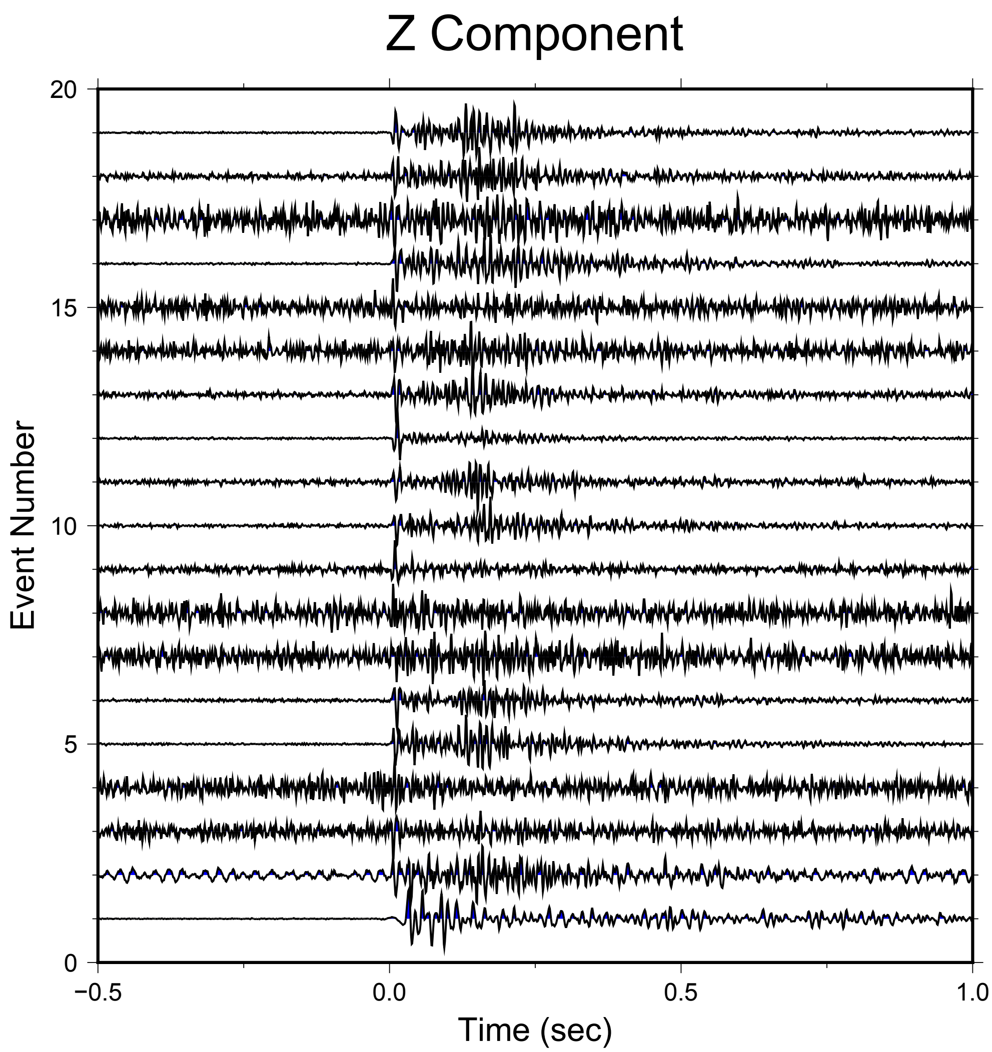

Figure 6: Vertical component waveforms for the 19 earthquakes detected by the STA/LTA detector.

The geophone data were also post-processed after the instruments were retrieved on 29 April. Processing of these instruments has included (i) automatic event detection using multiple algorithms and (ii) visual inspection during the time periods for the 19 events detected at the shallow borehole. In an attempt to automatically detect events during the stimulation period, we used a set of different regional and teleseismic detection algorithms developed to take advantage of the array geometry (Li et al., 2018; Linville et al., 2018; Meng and Ben-Zion, 2018). It was a challenge to apply these more regional scale methodologies to detecting events with M<0 at a very local scale. Also complicating the detection process in the time domain was the extremely noisy environment from operations and equipment on the well pad (e.g., generators, pumps). The algorithms flagged a few detections. However, we could not visually confirm these as microseismic events versus noise or determine detection criteria to apply to the entire dataset. We are currently exploring different approaches for array detection specific to the geometry and magnitude of these small events.

In a second approach to determine potential detection levels with the surface geophone array, we manually inspected the raw waveforms during the time periods for the 19 events detected by the shallow borehole. Five of the nineteen events (red stars, Figure 5; Schlumberger determined magnitudes M -1.171 to -0.519) were clearly observed and P- and S-phases were manually picked. An example is shown in Figure 7, where the P and S phases are picked on the vertical and horizontal components, respectively. It is evident that the amplitude of the different phases is at the noise level, which explains the unsuccessful application of detection algorithms in the time-domain.

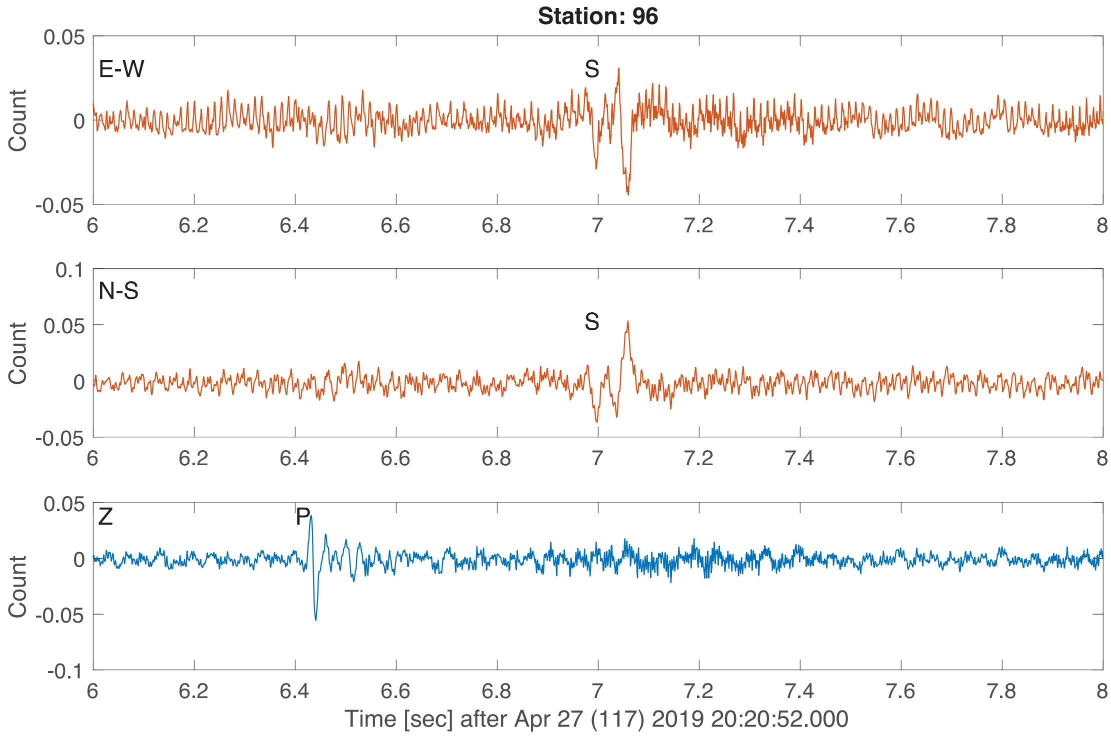

Figure 7: Example of M-0.7 seismic event recorded by station 96 located at the 3rd ring, 500 m from the well 58-32.

In summary, the geophone string detected events down to M -2, the iDAS and shallow borehole to M -1.5, the geophone array to M -1.2, and the URSN detections were more inconsistent. Going forward, it seems important to have deep geophone strings for detection and location of the smallest events. A combination of shallow boreholes and surface sensors could be designed to push detection levels below M -1 for consistent monitoring. The addition of DAS and geophone arrays deserve additional research emphasis. Given the relatively newness of DAS technology, more work is needed to bring this data into the monitoring realm, including ways to improve detection capabilities. Regarding geophone arrays, there is much promise in utilizing this data, especially for site characterization, but without telemetry it is not viable as a monitoring tool.

4. PLANS FOR FUTURE MONITORING

There are three key lessons learned from the stimulation test from April and May 2019 that will be considered as we move to establishing the permanent FORGE seismic network. Lessons include: (1) importance of optimal siting of the next seismic boreholes; (2) the benefit of different scales of monitoring; and (3) added benefits of including "research" instrumentation.

4.1 Borehole Geometry

The location for the two boreholes drilled for the stimulation experiment was largely informed by the need to demonstrate the detection of small seismic events within and above the granite reservoir. To meet this objective, the shallow borehole was located very close to the 58-32 well pad. Although data aquired during the stimulation were overwhelmed by environmental noise, there is still useable signal. However, much effort was needed to develop appropriate filters. A consequence of this was the data were not useful for near-real-time triggering and building of seismic events. Going forward the borehole instrumentation will be sited away from well-pad activities, and appropriate filtering will be implemented in the triggering algorithms.

A second issue regarding the geometry relates to detection and location of the smallest events. The distance from the injection areas to the borehole sensors in well 78-32 ranged from ~1000 - 1500 m and the ray paths were almost vertical. While not discussed in this paper there was substantial error in the seismic locations. To improve the event locations, we will consider sensors closer to the reservoir and at least one additional deep monitoring well to better constrain azimuthal variations.

4.2 Benefits of Scales of Monitoring

The importance of the deep borehole is clearly shown by the low event detection levels. However, due to sensor temperature restrictions continuous monitoring from these depths will be challenging. It is thus important to think about what seismic detection levels are needed for different phases of injection and shut-in. Thinking in terms of both shallow and deep boreholes will allow for more complete monitoring. Additionally, it is important to have a local surface network. Larger events will clip the downhole instrumentation. To retrieve important source information, on-scale recording will be needed. A second advantage of the surface network is the ability to monitor at a scale larger than the reservoir to guard against potential unforeseen fluid pathways.

4.3 Benefits of "research" instrumentation

The key instrumentation for monitoring the injection phase was the geophone string in the deeper borehole and telemetered seismic data. However, as we move forward, it is important to continue to deploy non-standard seismic instrumentation. Data and products collected from the iDAS and geophone arrays provide valuable information. Although the DAS had a higher detection level than the geophone string, the data contain important wavefield information that could be exploited for other uses. It could also be that the iDAS would have more complete monitoring if the cable was closer to the source zone.

Because the geophone array data processing is done post-injection, the data are not useful for real-time monitoring. However, with a dense array, event locations (representing the damage zone) can potentially be refined in between injection phases. Continued work is leading to improved detection levels from the geophone array. However, this work is still in progress.

5. CONCLUSIONS

The seismic networks deployed at the Utah FORGE site have provided useful information that will be used in the development of a permanent network. Based on numerical simulations and the results of the seismic monitoring, a second monitoring well will be drilled to a depth of ~1300 m north of well 58-32 and the planned trajectory of the deep injection well. A DAS cable will be installed in the new monitoring well. Borehole geophones will be installed for routine monitoring, and during stimulations multilevel geophone strings will be deployed. The downhole monitoring program will be supplemented with eight-to-ten shallow boreholes and surface arrays.

ACKNOWLEDGEMENTS

Funding for this work was provided by U.S. DOE under grant DE-EE0007080 "Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site". We thank Jim Rutledge and Thomas Coleman for collaborations in constructing the earthquake catalogs from Schlumberger and Silixa, respectively. We also thank Hao Zhang for implementing the STA/LTA for the shallow borehole data and J. Mark Hale for earthquake analysis. We thank the many stakeholders who are supporting this project, including Smithfield, Utah School and Institutional Trust Lands Administration, and Beaver County. A grant from the Utah Governor's Office of Energy Development has provided support for educational outreach activities. The Bureau of Land Management and the Utah State Engineer's Office have been very helpful in guiding the project through the permitting processes. We are especially grateful for the field support provided by Hao Zhang, Daniel Wells, Amy Record, Santiago Rabade, Kostas Gkogkas, Virgil Welch, Duane Winkler, and Mary Mann. Paul Roberson assisted in the preparation of the figures.

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