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Local Seismic Monitoring at the Milford, Utah FORGE Site

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ABSTRACT

The U.S. Department of Energy is proposing to develop a Frontier Observatory for Research in Geothermal Energy (FORGE). The goal for this facility is to develop and test new technologies and techniques related to enhanced geothermal systems (EGS). One of two potential locations for this facility (the Utah FORGE site) is located in the eastern Basin and Range in Utah's West Desert. One aspect of developing the FORGE facility is creating, in advance of any development, an induced seismic mitigation plan. A key aspect of this plan is establishing local seismic monitoring. For the Utah FORGE site, local seismic monitoring has been conducted at four scales using both variations in seismic network design and waveform matching approaches to enhance seismic event detection. From this monitoring, we conclude that earthquakes occurring in the vicinity of the Utah FORGE site are characterized by small magnitudes (most events are less than M 1.5), occurring at low seismic rates. Further, we find no evidence of seismic events within the boundaries of the proposed drill area. The seismic events tend to cluster to the east of the FORGE site in the Mineral Mountains or to the southwest in a region just north of the town of Milford, Utah.

1. Introduction

The U.S. Department of Energy is proposing to develop a Frontier Observatory for Research in Geothermal Energy (FORGE). The goal for this facility is to develop and test new technologies and techniques related to enhanced geothermal systems (EGS). A requirement for the FORGE project is to establish an Induced Seismic Mitigation Plan. In the guidelines for establishing the mitigation plan (Majer et al., 2012), a key component is developing local seismic monitoring. This monitoring should include a time period that spans both before and after the onset of operations. The information collected before allows for a baseline to be established that subsequent seismic events that occur after development can be compared. The monitoring should also establish a minimum magnitude of complete recording, M_{comp}, equal to magnitude 1.0, preferably M_{comp} of 0.0.

The proposed Utah FORGE site is located in the West Desert of Utah in Beaver County. This is a rural area. The nearest population center is the town of Milford, located 16 km to the southwest (Figure 1). The Utah FORGE site is included within the boundaries of the University of Utah Seismograph Stations (UUSS) monitoring region. UUSS has been monitoring seismic activity in Utah and the surrounding region for the past 50 years and collates an earthquake catalog that includes hypocentral locations and local (M_L) and/or coda (M_C) magnitudes (e.g. Burlacu et al., 2017). The catalog dates back to 1850. Analysis of the UUSS catalog for the time period 1 January 2000 to 30 June 2003 found an M_{comp} for the Utah FORGE site of 1.5 (Pankow et al., 2004). Since that analysis, regional seismic station coverage has improved in the region, and a local broadband network was installed in November 2016 (Figure 1). We currently estimate M_{comp} to be at or close to zero. There has been only one M > 4 earthquake in the greater Milford study area (Arabasz et al., 2015). This was the 1908 M 4.05 Milford earthquake located south of the town (Figure 1).

In this paper, we describe four levels of seismic monitoring at the Utah FORGE site based on seismic network configuration and seismic processing procedures. We use: (1) the UUSS seismic catalog to define seismic source areas; (2) waveforms from the events in the UUSS catalog as templates to enhance the catalog through subspace detection analysis; (3) data from a recently deployed local, broadband seismic array to lower seismic event detection levels; and (4) data from a temporary (one-month duration), dense seismic experiment centered on the Utah FORGE site to further search for small seismic events.

2. Seismic Monitoring

The four levels of seismic monitoring and the resultant catalogs are described in the following sections and are summarized in Figure 2.

2.1 Seismic Source Areas

Analysis of the UUSS catalog from 1981 through 2016 (without data from the FORGE specific broadband seismic network) shows that earthquakes near the Utah FORGE site tend to cluster in three areas. These three areas (Figure 1) locate near a quarry, the Milford airport, and in the Mineral Mountains. For these areas, there are 61 events, M 0.49 – 2.05, recorded from September 1997 to March 2015 in the Quarry box; 65 events, M 0.46 – 3.91, recorded from November 1995 through May 2001 in the Airport box; and 58 events, M 0.31 – 2.53, recorded from July 1981 through April 2011 in the Mineral Mountains box. Importantly for this area, before the installation of the FORGE broadband network the last seismic event cataloged was in March 2015.

Because of the proximity of the quarry, it is important to discriminate anthropogenic from natural seismicity. The quarry is an active open pit mine and regularly blasts the surrounding rock. Blasting in Utah is restricted to daylight hours. In comparing the time of day for the origins of the seismic events in each box (Figure 3), we find that for the Quarry box most of the events occurred exclusively in daylight hours. Only four of the 61 events appear outside of the expected times for blasting. Comparing this to the Airport and Mineral Mountains boxes, for which the

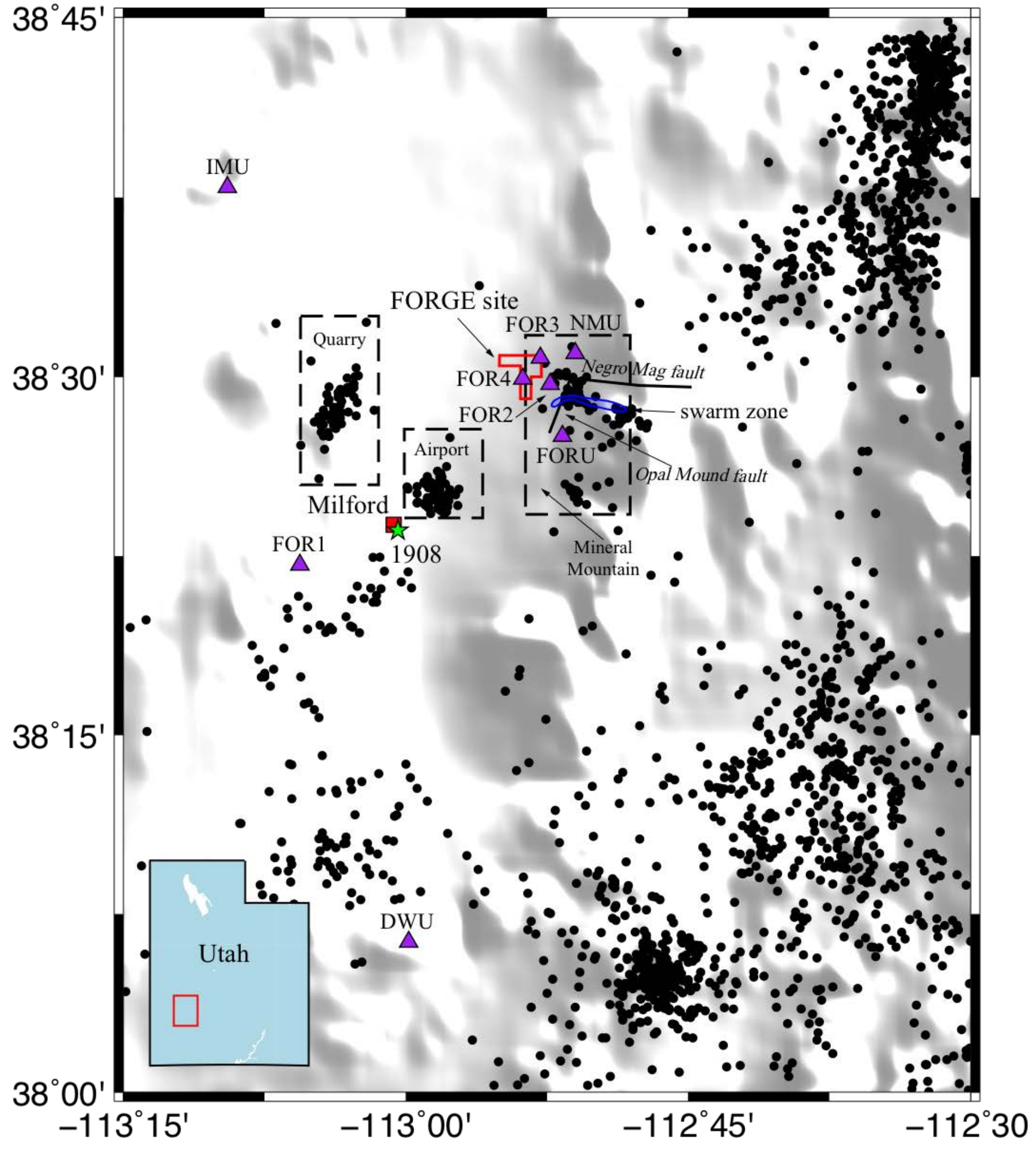

Figure 1. Study area map. Location of the Utah FORGE study area shown as red box in inset lower left corner. The proposed FORGE footprint shown by red polygon in main figure. Black dots, earthquakes (1981- 2016) from UUSS catalog. Green star, location of 1908 M 4.05 Milford earthquake. Black dashed boxes, locations of seismic source zones. Red square, location of Milford, Utah. Purple triangles, seismic stations; station names beginning FOR are part of the local broadband network. Black lines, local mapped faults. Blue polygon, swarm area defined by Zandt et al. (1982).

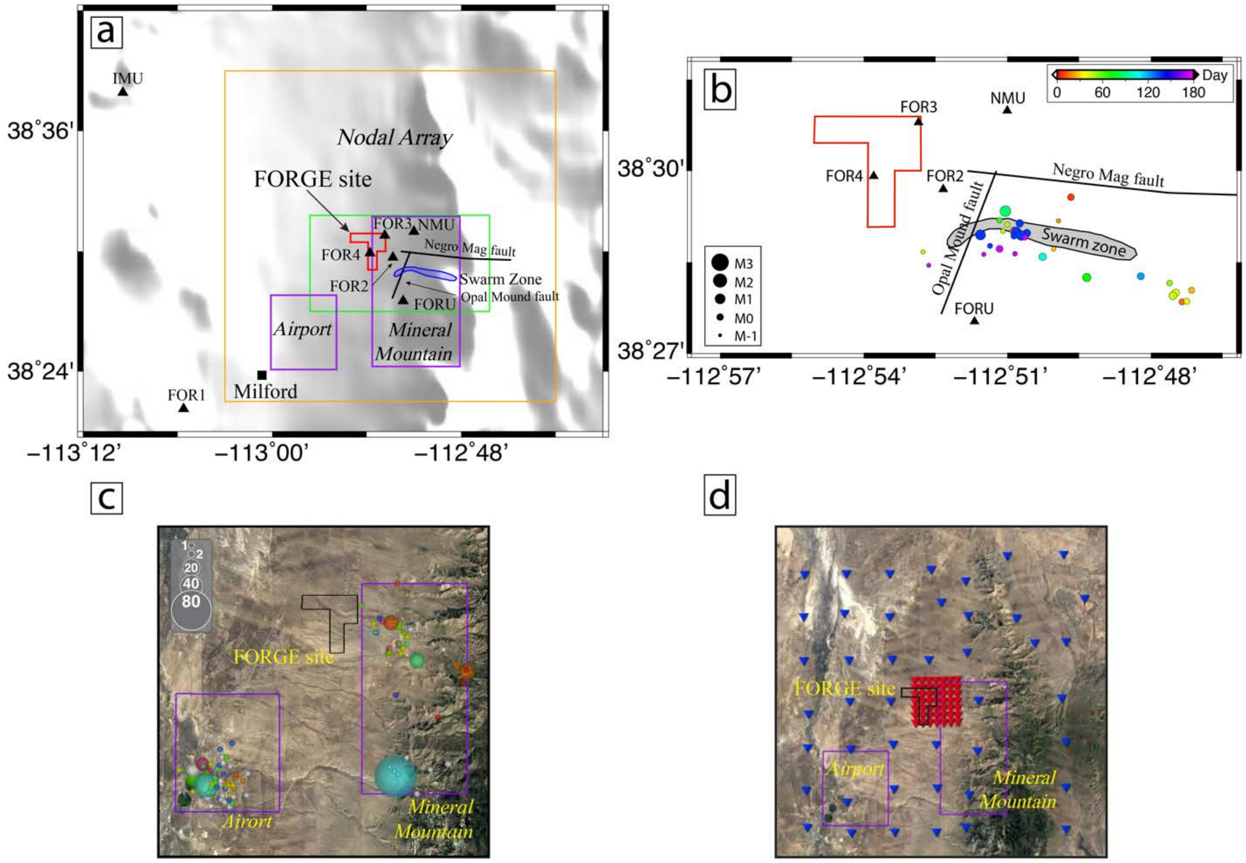

Figure 2. (a) Base map to show location of FORGE site (red polygon), faults (black lines), source areas discussed in sections 2.1 (purple boxes), station locations (black triangles), and the location of the Zandt et al (1982) swarm (blue polygon). (b) Enlarged section (green box in (a)) showing the location of earthquakes identified using the broadband network. The color of each event shows the progression in time beginning November 14, 2016. (c) Location of the templates used in the subspace analysis. Color indicates subspace group. Size of the circle, number of detections that best correlate with that template. (d) Geophone locations for the Nodal seismic experiment (yellow box (a)). Dense grid centered on FORGE site, station spacing ~0.6 km. Outer grid, station spacing ~4 km.

events occur throughout the 24-hour window, it is clear that the seismicity located in the Quarry box is predominantly, if not exclusively, due to anthropogenic sources (blasting from the collocated quarry). Since the seismic activity in the Quarry box is not tectonic in nature it was removed from further analysis. By looking at the resultant time history of natural seismicity in the study area captured in the UUSS catalog (blue symbols, Figure 4), it is clear that seismicity rates for the FORGE area at M_{comp} of 1.5 are quite low.

2.2 Subspace Detection Analysis

Using data collected by the regional seismic network, we employed subspace detection analysis to improve the completeness of the earthquake catalog for the time period that additional seismic stations were not available. Subspace analysis (Harris, 2006; Harris and Paik, 2006) uses singular value decomposition (SVD) to decompose a cluster of similar waveforms into basis vectors.

These basis vectors are then scanned against continuous data in order to find new events that belong to the same family.

We use the program *Detex* (Chambers et al., 2016) to implement the subspace detection analysis. For this, we created two sets of templates. For the Airport box there were 55 template events and for the Mineral Mountains 42 templates. Waveforms from each set of template events recorded at stations NMU, IMU, DWU (Figure 1) were correlated by station against all other templates in the set, and linked into subspace groups using single-link clustering (Harris, 2006). Based on the cross-correlation value not all events clustered into a family, as their similarity was too low with the other waveforms. These events we call singletons. The basis vectors and singletons are then correlated against continuous data for the same stations for the time period 2010 through 2016. All UUSS seismic data are archived at the Incorporated Research Institutions for Seismology (IRIS) data management center (DMC).

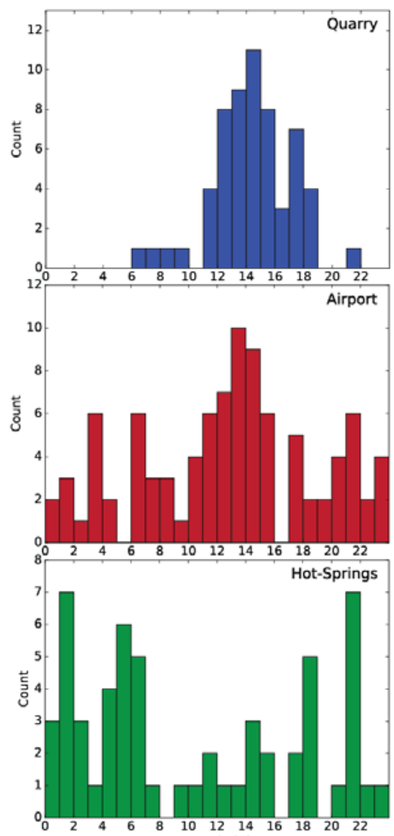

Figure 3. Time of day histograms for events locating within each of the three focus areas (Figure 1). Note that seismic events from the quarry box occur almost exclusively during daylight hours.

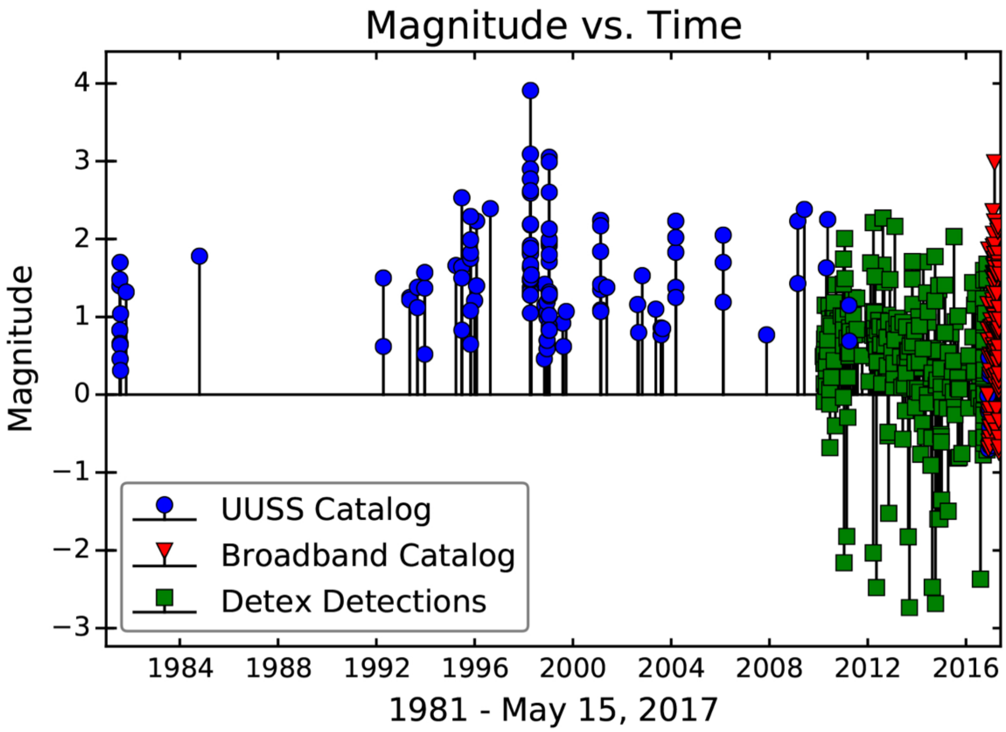

Figure 4. Magnitude time history for earthquakes located in proximity to the Utah FORGE site. Blue symbols, earthquakes in UUSS catalog before the addition of the local broadband network. Green symbols, earthquakes detected using subspace detection. Red symbols, earthquakes located after the installation of the broadband network.

Using a detection threshold for which the likelihood of producing a false detection due to random noise calculated from 100 hours of data is 10^{-12} (calculated separately for each station), requiring that at a minimum of two stations detect the same event, and manually reviewing all resulting detections, identified 110 new events in the Airport box and 153 new events in the Mineral Mountains box (Figure 2c and Figure 4). From this analysis, we learn that seismic events were occurring below the UUSS detection threshold for the time period that no events were being cataloged by UUSS. We also were able to push M_{comp} levels closer to zero. However, and importantly, subspace like any waveform matching technique, can only detect events similar to the template events. This technique cannot be used to identify new source regions, so any M_{comp} conclusions are just based on the previously identified sources.

2.3 Local Broadband Seismic Network

In mid-November 2016, five broadband seismometers with near-real-time telemetry were integrated into UUSS operations in order to monitor seismicity in the Utah FORGE area (stations beginning FOR, Figure 2). An earthquake with a magnitude large enough to be recorded by at least four stations typically triggers the automatic system and produces a preliminary location. Subsequently, a seismic analyst manually picks *P*- and *S*-arrivals and relocates the earthquake. If possible, the local magnitude (M_L) or coda (M_C) magnitude are also estimated for the earthquake. In this way, we have identified 32 earthquakes (M -0.74 to 1.15) with welldetermined locations through May 15, 2017 as shown in Figure 4b. Previous to the installation of the broadband network, the last earthquake in the UUSS catalog located in the Mineral Mountains box or the Airport box occurred in 2011. It is clear (Figure 5) that at least in the Mineral Mountains area there is on-going seismic activity below the detection threshold of the UUSS regional seismic network.

The earthquakes located with the broadband network mainly locate in a nearly E-W striking zone under the Mineral Mountains to the east of the FORGE site. This zone basically overlaps with the one in which 1044 micro-earthquakes ($M_L \leq 1.5$) were detected by Zandt et al. (1982) (Figure 2). However, the current events are slightly elongated in the E-W direction compared to the Zandt source area. Of the 32 events detected, 13 appear to have occurred in two swarm sequences. The first swarm is comprised of eight earthquakes occurring on March 26, 2017 with the largest magnitude of M 0.96 (dark blue circles Figure 2b). The second swarm is comprised of five earthquakes occurring on May 03, 2017 with largest magnitude of M 0.47 (purple circles, Figure 2b). Both swarms are located in the western part of the swarm zone defined by Zandt et al. (1982).

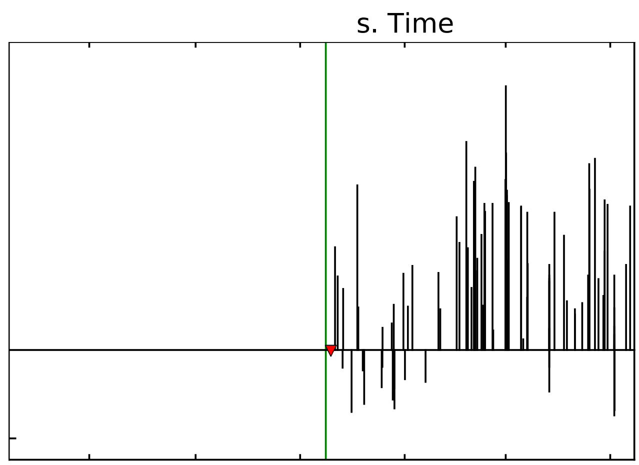

Figure 5. Magnitude time history for events in the UUSS earthquake catalog. Events shown were detected and located after the installation of the local broadband network. Green line, shows installation date of local broadband network. Note that the previous event in the earthquake catalog is from 2011.

2.4 Nodal Seismic Experiment

To further characterize seismicity near the FORGE site, a three-component, 96-element, Nodal 3C 5Hz array (Figure 2d) was deployed from December 13, 2016 through January 15, 2017. The array was composed of two subarrays: one with geophone spacing of ~4 km and the second with a geophone spacing of ~0.6 km. Both arrays were centered at the FORGE site. This data set has been analyzed using a frequency domain seismic event detector (Linville et al, 2014). A total of 57 earthquakes were identified with this method and most locate near the Opal Mound fault. However, locations are preliminary and because of the detection method are subject to large errors. Relocation of three events that originally located close to the FORGE site using *P*-arrival times found that the events actually locate several kilometers to the east in the Mineral Mountains.

3. Conclusions

Using four scales of seismic event detection, a baseline for local seismic event monitoring for the Utah FORGE site has been established. Naturally occurring seismicity near the Utah FORGE site occurs in two general areas: (1) to the east under the Mineral Mountains and (2) to the southwest near the Milford airport. There is also a zone of anthropogenic (blasts) sources to the west of the FORGE site. There is no evidence of seismic activity under the Utah FORGE site. East of the Utah FORGE site there is a prominent east-west structure, first identified by Zandt et al. (1982), where earthquake swarms appear to be prevalent. In conclusion, seismicity near the Utah FORGE site occurs in two zones and is characterized by low rates and low magnitudes.

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