MICRO-SEISMIC CHARACTERIZATION OF THE UTAH FORGE SITE

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ABSTRACT

The University of Utah Seismograph Stations (UUSS) has been monitoring seismic activity in Utah and the surrounding region for over 50 years and has compiled an earthquake catalog going back to 1850. Based on this catalog and the results of a temporary seismic network operating in 1981, the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) study area was characterized by small magnitude earthquakes occurring at a low seismic rate. To better understand seismic patterns and characteristics, the events in the UUSS catalog were relocated using updated velocity models, analyzed for time of day patterns, and waveforms from individual event clusters were used to identify source zones. In addition, to lower the magnitude of completeness, both a five-station local broadband network and two Nodal geophone temporary deployments were installed centered on the proposed FORGE site. Subspace detection analysis was also utilized to identify small seismic events using events from the UUSS catalog as templates. From these analyses and experiments, we identified three seismic source zones. The first source zone northwest of Milford, Utah, is located near an active quarry and contains seismic events that all occur during daylight hours. We conclude that these events are anthropogenic in origin. The second source zone is located near the Milford airport. This zone hosts the larger events in the study area, including possibly the largest event, the 1908 M 4.05 Milford earthquake. The third zone includes the Mineral Mountains. Most seismicity in this zone occurs in an east-west band to the east of the FORGE site. Notably, events detected with the local broadband and geophone arrays are located in the same source zones identified from the UUSS catalog, and no events were located within the proposed FORGE footprint.

INTRODUCTION

Seismicity induced by industrial activities has been known and studied for many years (e.g., Raleigh et al., 1976; Hsieh and Bredehoeft, 1981). With both increased and changing activity in energy sectors and the migration of some of these activities toward more populated areas, reporting and concern about induced seismicity has dramatically increased (e.g., Petersen et al., 2017). Often cited examples of the increased frequency of induced seismicity and the societal impacts resulting from these events include the rapid increase of M > 3 earthquakes in Oklahoma beginning in 2001 (Ellsworth, 2013) and the Basel, Switzerland, M 3.7 earthquake (Deichmann and Giardini, 2009; Bachmann et al., 2011). With an increase in induced seismicity worldwide (Foulger et al., 2017), it is important to assess, and make plans to mitigate, the risk of induced seismicity prior to activities that might lead to these earthquakes (e.g., Majer et al., 2012; Walters et al., 2015; Trutnevyte and Wiemer, 2017). An important step in assessing the potential risk and then for subsequent monitoring is to characterize the local seismicity prior to industrial activities, creating a baseline to which subsequent events can be compared. This paper describes the analyses used to establish the baseline for local seismicity near the Utah Frontier Observatory for Research in Geothermal Energy (FORGE).

The Utah FORGE site is located in a rural area in the West Desert of Utah in Beaver County. The nearest population center is the town of Milford, located 16 km to the southwest. 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 over 50 years and has compiled a historical earthquake catalog dating back to 1850 (Figure 1; Arabasz et al., 2015). Based on this historical record, there was only one M > 4 earthquake in the greater Milford, FORGE study area (yellow box Figure 1), namely the Milford earthquake M 4.05 event in 1908. Within ~50 km of the proposed FORGE site there are additional earthquakes M < 4.9, and one earthquake M ≥ 4.9, the 1901 M 6.6 Tushar Mountain earthquake (#2, Figure 1) located ~50 km to the east. Beginning in 1981, UUSS transitioned to cataloging digital data from the regional seismic network. Analysis of the UUSS earthquake catalog for the time period 1 January 2000 to 30 June 2003 found a minimum magnitude of completeness (M_{comp}) for the Utah FORGE site of 1.5 (Pankow et al., 2004). In subsequent work, Potter (2017) using only UUSS catalog data local to the Utah FORGE site determined an M_{comp} for the Utah FORGE site of 1.7.

In addition to regional monitoring, two local seismic studies recorded events near the Utah FORGE site. Olson (1976) analyzed the seismicity located in known geothermal resource areas (KGRA) in central Utah. For the Roosevelt Hot Springs KGRA located due east of the Utah FORGE site in the Mineral Mountains, six earthquakes were recorded on the west flank of the Mineral Mountains. Olson (1976) concluded that the Roosevelt Hot Springs KGRA is characterized by low seismic rates. They attributed these low rates to either high seismic detection levels or the result of localized high temperatures.

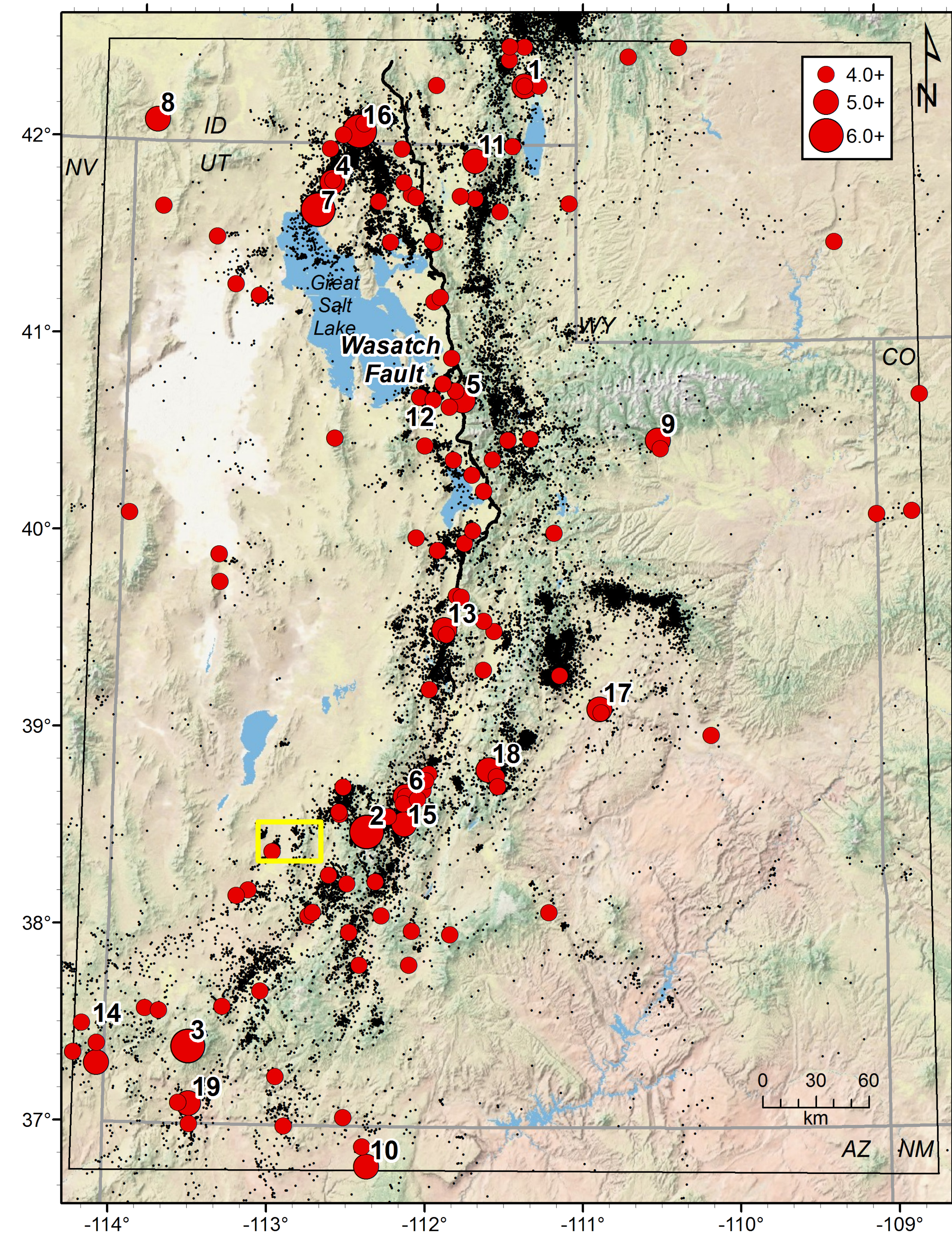

Figure 1. *Epicenter map of mainshocks of moment magnitude* ***M*** *> 4.0 in the Utah Region, 1850 through September 2012 (red dots); foreshocks, aftershocks, and mining-related seismicity are excluded. Data are from a revision of Utah's historical earthquake catalog (Arabasz et al., 2015). The small black dots show all earthquake epicenters in the UUSS earthquake catalog, July 1962 through December 2012. The numbers correspond to significant earthquakes discussed in Arabasz et al. (2015). The yellow box encompasses the FORGE study area.*

In a second experiment to characterize background seismicity prior to production at Roosevelt Hot Springs Blundell Geothermal Plant, Zandt et al. (1982) installed a local seismic array to characterize the background seismicity. During the approximate two-year deployment (September 1979–January 1982), they concluded that there are few earthquakes M > 2. However, they did capture one energetic seismic swarm (1044 earthquakes M ≤ 1.5) from June through August 1981. This swarm occurred east of the present borefield at the Blundell Power Plant, primarily in the Mineral Mountains (Figure 2). The seismicity trend of this swarm was mostly east-west. They concluded that the swarm was primarily naturally occurring and was consistent with either (or both) seismicity occurring along the projection of the east-west-trending Negro Mag fault or along northwest-trending faults mapped by Nielson et al. (1978; Kirby, 2019).

Based on these prior works, seismicity near the Utah FORGE site was known to be low-magnitude, occurring at low seismic rates with possibly a tendency for low-magnitude (below regional network detection levels) seismic swarms. To establish a baseline for these small-magnitude events, we installed a local broadband network and two stand-alone dense short-period digital Fairfield Nodal seismic arrays centered on the FORGE footprint. Additionally, we applied detection algorithms to continuous UUSS regional seismic data from 2010 through 2016.

To establish the baseline seismicity levels for the Utah FORGE site, we examined the location, magnitude, and seismic rates for earthquakes detected and located by the UUSS regional seismic network (01/01/1981–10/31/2016) and added catalogs compiled as part of the FORGE study. Consistent with previous studies, we conclude that this area is characterized by low seismic rates and low magnitudes. Additional events detected with the local networks deployed for the FORGE study and from enhanced detection methods were located in the same general areas as the events in the UUSS regional catalog. Importantly, no events were located within the areal footprint of the proposed FORGE site.

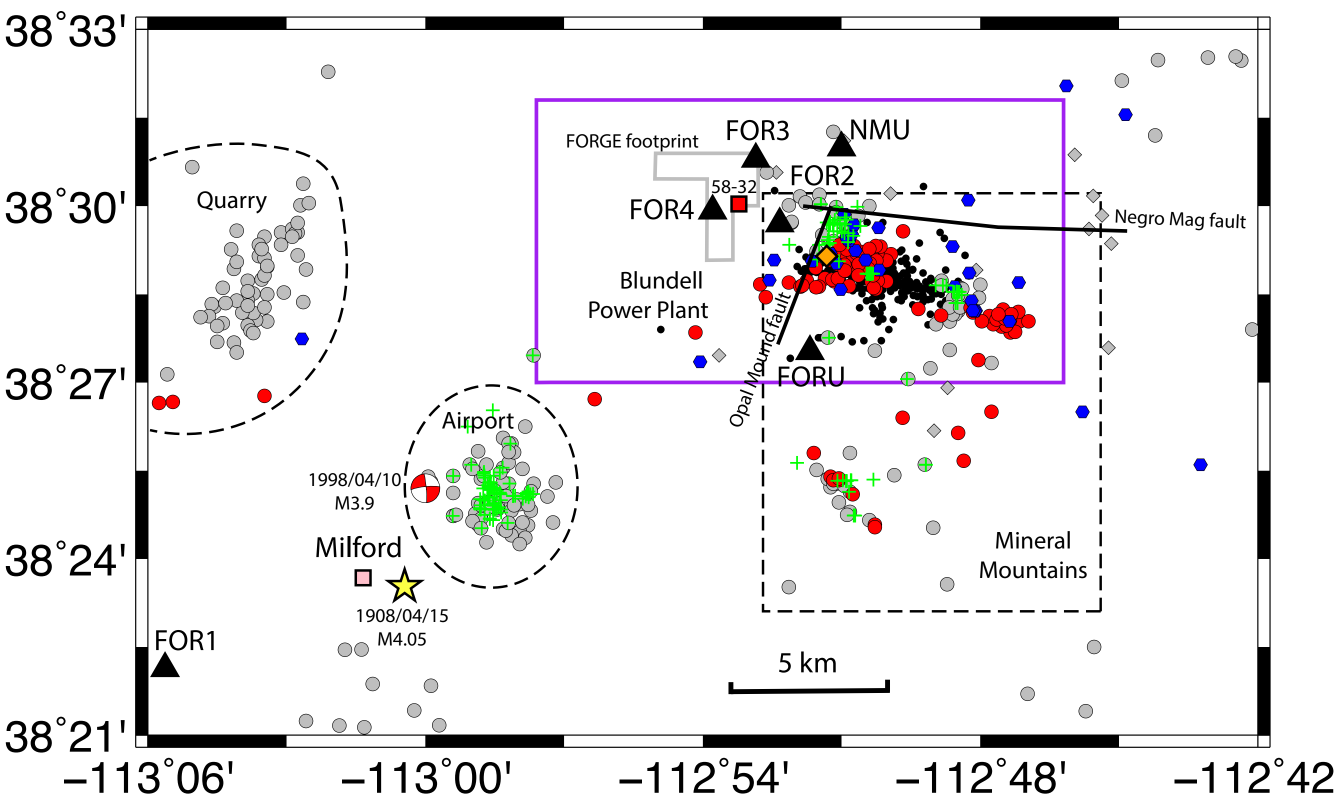

Figure 2. *Utah FORGE earthquake catalog. Gray circles, earthquakes from the UUSS catalog 1981–2016 relocated with an updated velocity model. Red circles, earthquakes located after installation of the broadband network. Blue hexagons, earthquakes detected with the Nodal array. Gray diamonds, earthquakes from Olson (1976). Black circles, earthquakes from Zandt et al. (1982). Green crosses, earthquakes identified using subspace analysis. Dashed polygons denote the three source zones discussed in the text. Black triangles, locations of seismic stations. Purple region, area shown in Figure 7. Gray polygon, region defined as FORGE footprint.*

SEISMIC MONITORING

UUSS Regional Catalog

In support of the Utah FORGE project, events in the UUSS catalog (1981–2016) were relocated using updated velocity models, with depths set relative to sea level (Figure 2). The relocation of these events caused slight changes in location, and overall resulted in tighter spatial clustering. No earthquakes, during this time period, were located within the proposed FORGE footprint (Figure 2). During the study period, earthquakes occurring outside the Utah FORGE footprint ranged in magnitude from M -0.09 to 3.91. The average horizontal and vertical 90% confidence errors for these earthquakes are 0.9 km and 4.9 km, respectively. Spatially, there are three distinct clusters: (1) northwest of Milford, (2) northeast of Milford, and (3) scattered seismicity in the Mineral Mountains (Figure 2).

Waveform analysis and event timing indicate that events in the northwest cluster (labeled Quarry, Figure 2) are quarry blasts, not tectonic earthquakes. Evidence for this conclusion includes their epicentral proximity to quarries (conspicuous on Google maps), small magnitudes (M 0.49 to 2.05), shallow depths, restricted timing (all events occur during daylight hours, Figure 3), and highly correlated waveforms implying a similar location and source mechanism.

The second cluster is located northeast of Milford near the Milford airport and is not far from the M_W 4.05 1908 Milford earthquake (Figure 2). The magnitudes in this cluster range from M 0.46 to 3.91, and the events occur throughout the day (random timing, Figure 3). This cluster seems to host the largest events in the region and the events are interpreted as tectonic in origin. The moment tensor for the M 3.9 event indicates a strike-slip mechanism and relocation of the seismicity in this cluster (Potter, 2017) is consistent with a north-south-striking fault plane.

Events in the third cluster located in the Mineral Mountains also occur throughout the day (random timing, Figure 3). Spatially, there is a clustering of events around the Opal Mound fault, distributed on the eastern edge of the Zandt swarm region and to the south of station FORU (Figure 2). While these events are most consistent with a tectonic origin, given the proximity to the Blundell Power Plant, induced seismicity may be a secondary source type.

Few events were located from April 2011 through August 2016 within the study area (Figure 4). To explore this quiescence period, we employed subspace detection analysis (Potter, 2017). 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., 2015) to implement the subspace detection analysis. For this, we created two sets of templates. For the airport region, we used 55 template events and for the Mineral Mountains 42 templates. Waveforms from each set of template events recorded at UUSS regional stations NMU, IMU, and DWU 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 the waveform similarity with the other waveforms in these cases was too low. These events are called singletons. Both basis vectors and singletons are correlated against continuous data for the same stations, for the time period 2010 through 2016. This analysis detected 61 seismic events in the Mineral Mountains region (M -0.55 to 1.52) and nine events in the airport region (M -1.49 to 0.91). These events are below the M_{comp} determined for the regional network.

Waveform clustering analysis (Potter, 2017) identifies several distinct clusters of seismic events in the Mineral Mountains area. Based on the different clusters and the proximity to the Blundell Power Plant, we investigated possible correlations with the pumping history at that power plant. We found no observable connection between the events cataloged in the area and the injection/withdrawal history of the power plant (Figure 5). The plant was completed in 1984 and although the pumping history is not available prior to 1992, there is only one event cataloged from 1984 (completion of the plant) to 1992. The plant opened a binary power plant in 2007, allowing more heat to be pulled from the recovered fluids. Even with this change in activity, no change is evident in the seismic activity.

Local Broadband Network

In November 2016, a five-station broadband seismic network was installed (Figure 2). Three stations were located on-top or in close proximity to the FORGE footprint. A fourth station was located on bedrock in the Mineral Mountains southeast of the FORGE footprint. The fifth station was located on bedrock southwest of Milford. The fifth station was selected to provide better azimuthal control to the seismic locations. These stations together with UUSS regional station NMU, located to the northeast of the FORGE footprint in the Mineral Mountains, form the local array for the Phase 2 FORGE project. Data from this local array

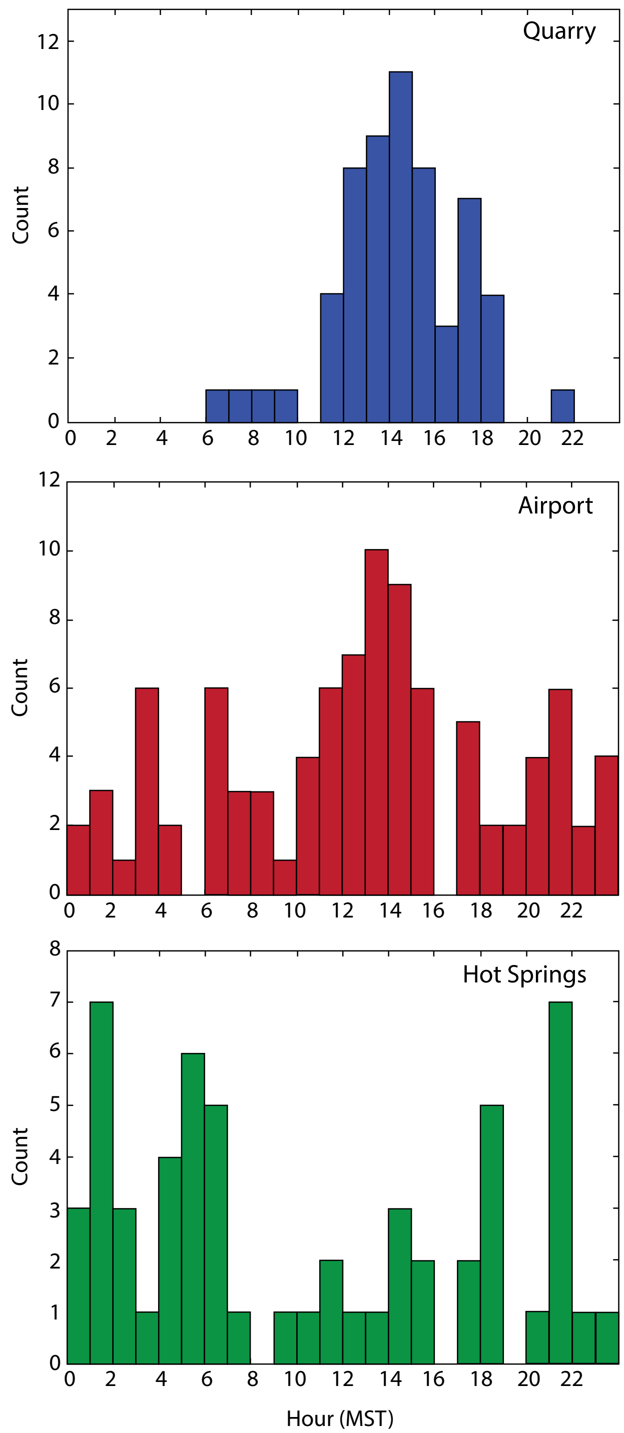

Figure 3. *Time-of-day histograms of events in each of the three source zones shown in Figure 2. Quarry, located northwest of Milford, Utah. Airport, located northeast of Milford, Utah. Hot Springs, events occurring in the Mineral Mountains.*

and from the regional seismic network were combined to locate and estimate magnitudes for new seismic events. The goal of this array was to reduce the M_{comp} to 0 or lower.

The local seismic array installed for the FORGE project combined with nearby UUSS regional seismic stations greatly improves the seismic detection level for the study area. Figure 6A shows that most detections after the installation of the broadband array are well below the regional network M_{comp} of 1.5 to 1.7. We estimate a revised M_{comp} of around 0.0 for the FORGE area (Figure 6D). Because there are stations closer to the source zones, 90% confidence location errors decreased to 0.7 and 3.9 km for horizontal and vertical, respectively. Spatially, most of the seismic events were located east of the Opal Mound fault primarily in or near to the Zandt swarm region (Figure 2). There is also a small cluster in the southern Mineral Mountains source zone.

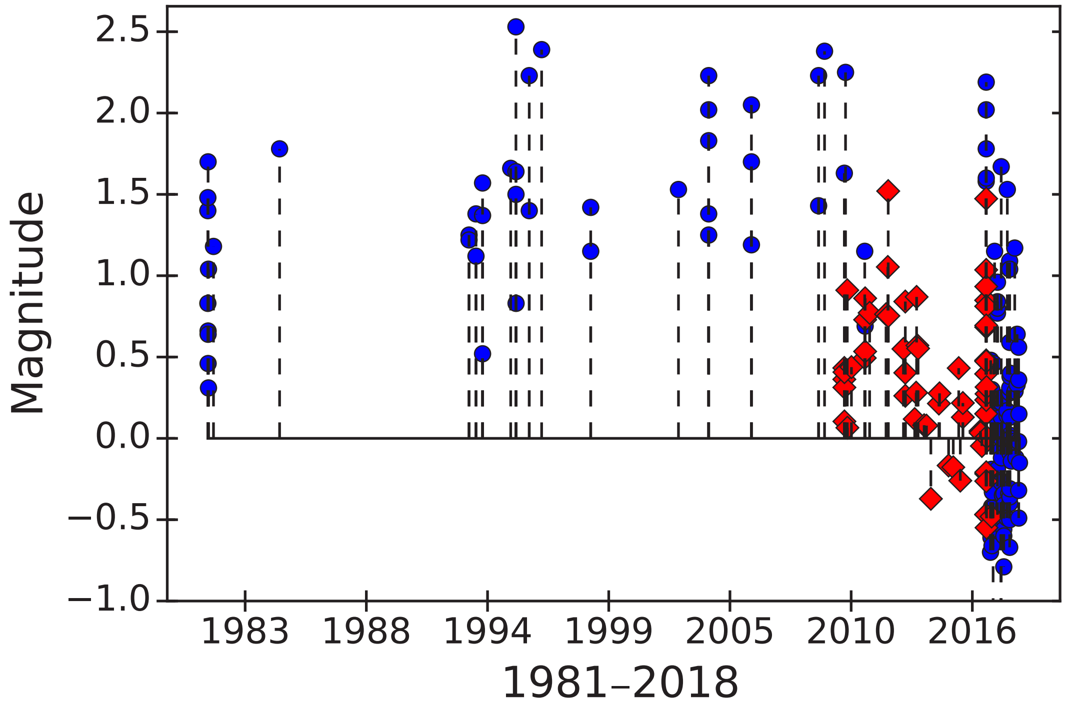

Figure 4. *Magnitude-time history for events in the UUSS catalog (blue circles). For the time period 2011 to 2016, there were no events in the regional catalog. However, 70 events below the regional* M_{comp} *were identified using subspace analysis (red diamonds).*

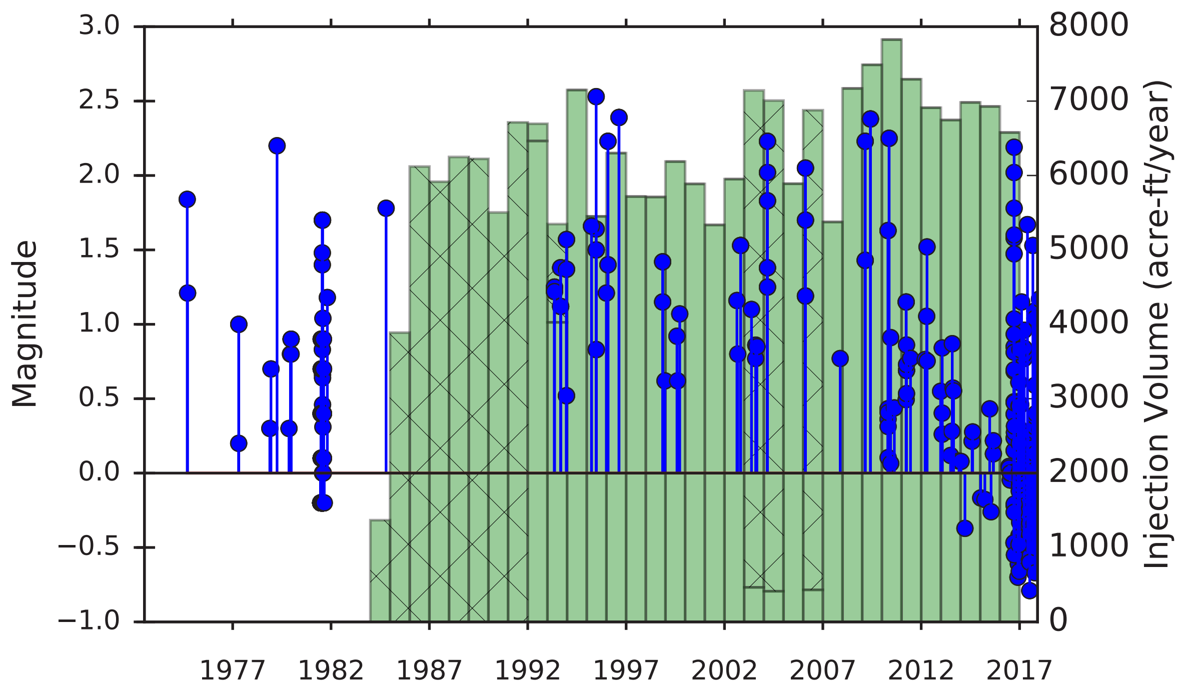

Figure 5. *Seismicity (blue circles, left axis) versus pumping history for the Roosevelt Hot Springs geothermal plant (green bars, right axis). Pumping history from published data from waterrights.utah.gov. Hashed green bars (right axis), pumping history adjusted based on the reported power produced and discrepancies in the reported fluid production.*

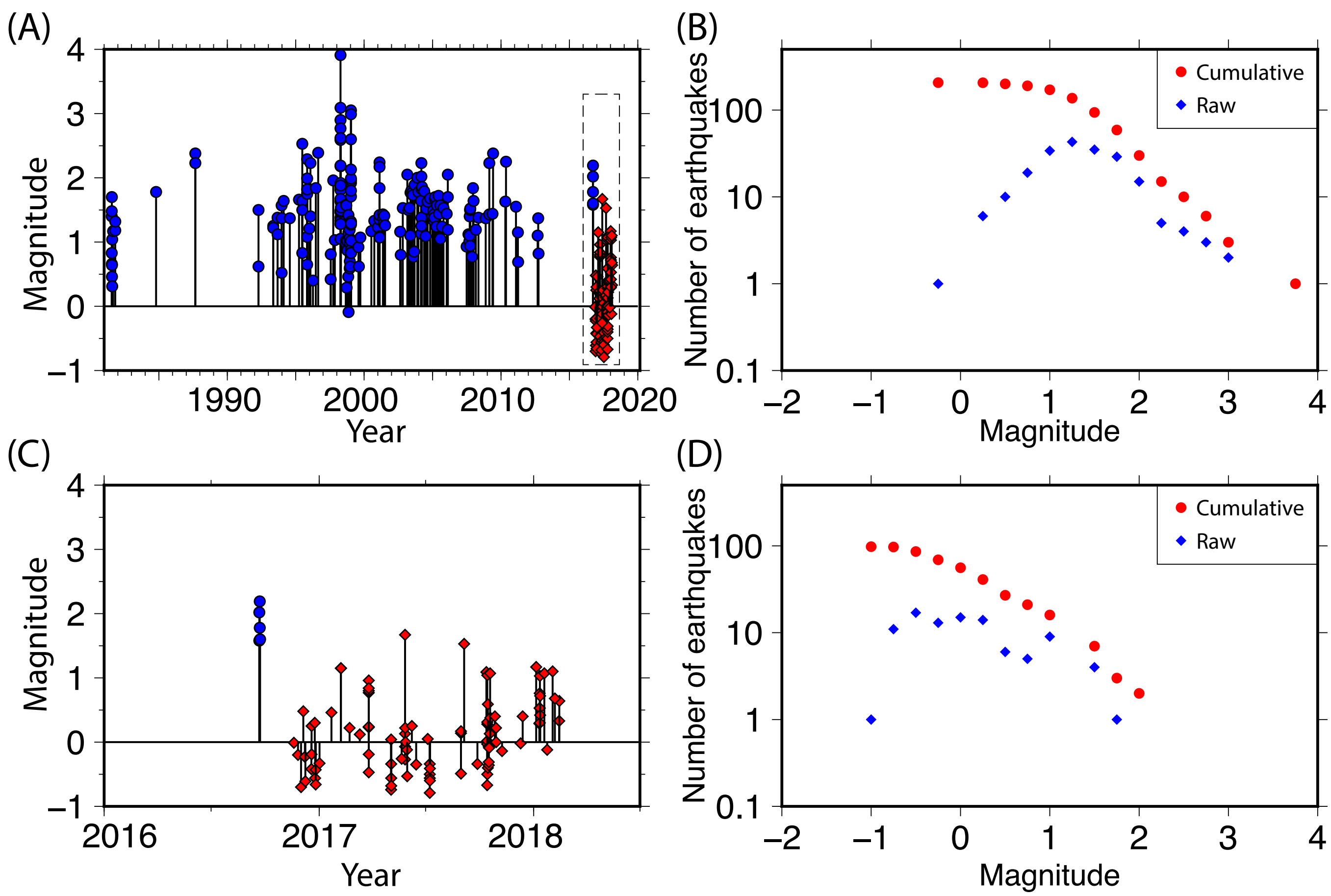

Figure 6. Magnitude-time plot for events in the UUSS catalog before (blue) and after (red) the broadband network was installed. ***(A)*** *Full time period of the catalog.* ***(B)*** *Magnitude distribution of numbers of events for time period shown in* ***(A)****.* ***(C)*** *Magnitude-time distribution for events since 2016.* ***(D)*** *Magnitude distribution of numbers of events for time period shown in* ***(C)****.*

Short-Term Geophone Experiments

In addition to the local broadband network, two ~one-month long deployments of three-component Fairfield Nodal geophones were installed to further enhance seismic detection levels. The first Nodal array was installed in December 2016 and consisted of 93 stations, 49 with ~650 m spacing directly above the Utah FORGE footprint and the remaining 44 distributed with ~4.5 km spacing surrounding the FORGE site. The small aperture dense array above the FORGE site was reoccupied on August 18, 2017, for 32 days. Using this dataset 42 events (M -0.5 to 0.5) were added to the FORGE catalog (Trow et al., 2018). The majority of these events were located in the region defined by the Zandt swarm zone.

RESULTS

Using multiple scales of seismic monitoring and advanced detection analysis (subspace), we identified three source zones in the larger Utah FORGE study area (Figure 2): (1) a zone located northwest of Milford, Utah, composed of primarily anthropogenic sources; (2) a zone located northeast of Milford, Utah, consistent with a roughly north-south-striking nodal plane determined from the moment tensor of an M 3.9 strike-slip earthquake; and (3) a zone located in the Mineral Mountains. Within the Mineral Mountains most events occur within a roughly 5-km-wide east-west-striking area originally identified by Zandt et al. (1982) with a smaller cluster of events located south of station FORU. The events located in the Zandt swarm zone (Figure 7) are separated into two distinct clusters: a shallow cluster located near the power plant production zone and a deeper cluster to the east, which appears to dip toward the west. No new source areas were identified as a consequence of lowering the detection level from M_{comp} 1.7 to 0.0, and no events were detected within the FORGE footprint. Additionally, no additional energetic (N > 25) swarms have been recorded since the 1982 swarm.

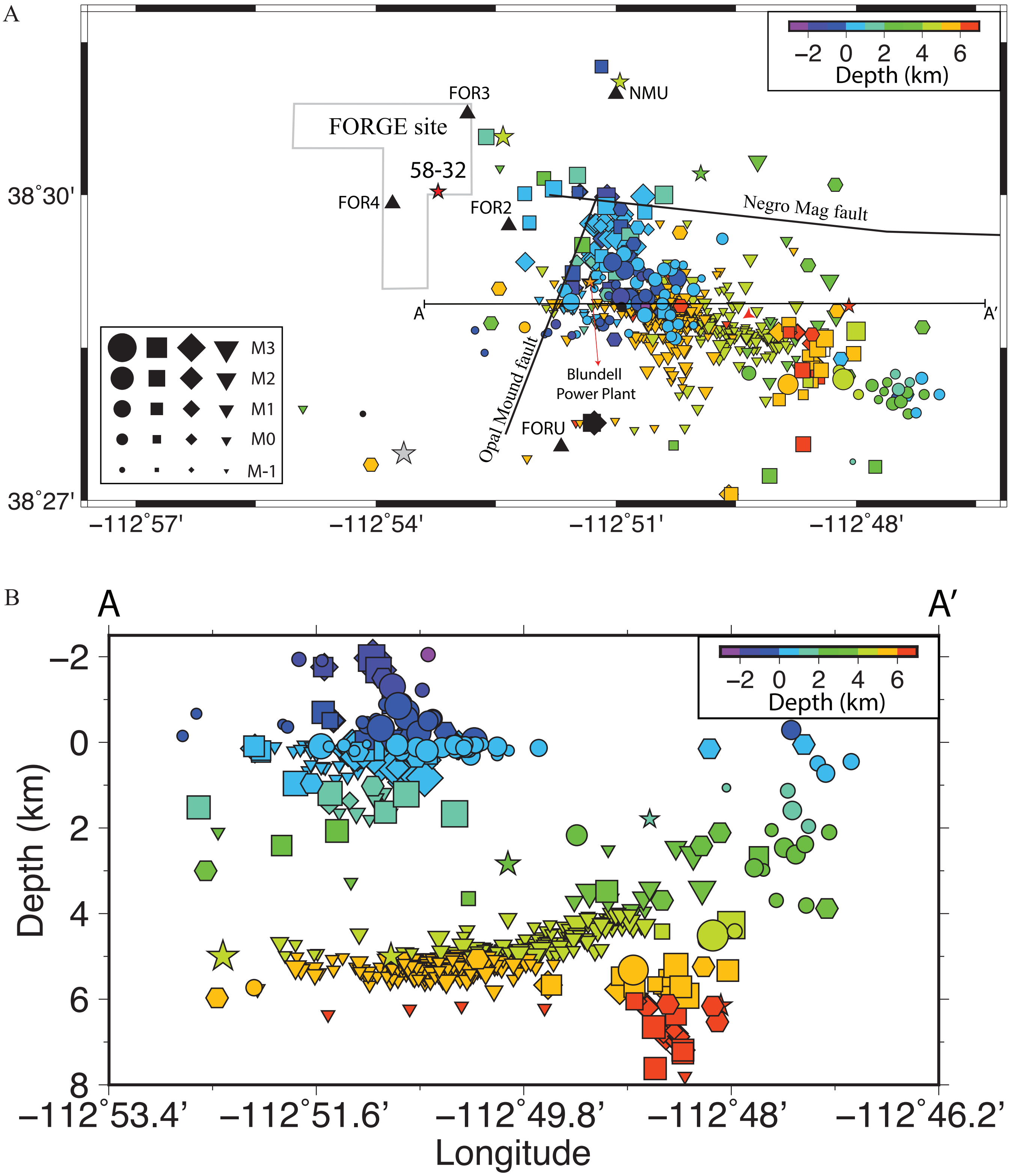

Figure 7. ***(A)*** *Utah FORGE earthquake catalog. Circles, earthquakes from the UUSS catalog 1981–2016 relocated with an updated velocity model. Squares, earthquakes located after installation of the broadband network. Hexagons, earthquakes detected with the Nodal array. Stars, earthquakes from Olson (1976). Inverted triangles, earthquakes from Zandt et al. (1982). Diamonds, earthquakes identified using subspace analysis. Black triangles, locations of seismic sensors. Gray polygon, region defined as FORGE footprint.* ***(B)*** *Seismic events shown in Figure 7**(A)** collapsed onto an east-west cross section (A–A'). Depth is relative to sea level.*

CONCLUSIONS

Based on the multiple levels of seismic monitoring, we conclude that (1) no naturally occurring seismic events were located within the Utah FORGE footprint; (2) seismicity occurs at low rates and events have low magnitudes, typically $M < 1.5$; and (3) most seismic events in the larger FORGE study area occur under the Mineral Mountains to the east of the Opal Mound fault with a less pronounced source zone near the Milford airport.

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