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Seismic Monitoring at the Utah FORGE EGS Site

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ABSTRACT

The Utah FORGE seismic monitoring plan provides infrastructure for two purposes: first, to continuously monitor seismicity as a part of mitigation strategies for potential seismic hazards associated with fluid injection and migration over the larger FORGE footprint, and second, to monitor during stimulation or injection operations as a diagnostic for mapping and characterizing the fracture systems created and activated for reservoir development. The former need involves an array of surface and shallow borehole receivers. The latter need is achieved with deep-borehole, multi-level, high-temperature receiver systems. Both monitoring systems will provide continuous coverage through all field activities, including before, during, and after all injection operations and flow testing.

For monitoring of potential seismic hazards, the goal is to achieve a magnitude-of-completeness of M 0 with detection capabilities down to M -1.5. The previous surface network at FORGE was capable of detecting and locating events down to M -1 in the Mineral Mountains 10 km east of FORGE. Improvement was made by reconfiguring the station placement and supplementing the network with combined broadband accelerometer stations placed in 100 to 150 ft boreholes. The improved coverage and sensitivity allow: (1) tracking changes in earthquake statistics; (2) tracking event migration within and outside the FORGE footprint; and (3) the analysis of source properties for the larger events.

Placement of the deep monitor wells was guided by modeling efforts to optimize source location accuracy for the initial stimulation plans. High-temperature, 3-component, borehole receiver strings will be deployed in three wells at or near reservoir depths. The deep-well receiver strings for monitoring during stimulations will be supplemented with downhole DAS, a new 3-component fiber-optic borehole array, and a high-density array of surface receivers.

1. Introduction

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) project is a test site for demonstrating technologies for engineered geothermal systems (EGS) (Moore et al., 2020). EGS involves the creation of sustainable rock permeability in the subsurface reservoir in order to extract heat, carried out by water injection stimulation to create or enhance fractures along favorably oriented trends of weakness in the rock. Seismicity induced by such stimulation must be monitored both to map the EGS reservoir growth and to mitigate possible seismic hazards (Majer et al., 2012). Hence, the seismic monitoring at the Utah FORGE is to be conducted at two scales under a plan that provides infrastructure for two purposes: first, to continuously monitor seismicity as a part of mitigation strategies for potential seismic hazards associated with fluid injection and migration over the larger FORGE footprint, and second, to monitor during stimulation or injection operations as a diagnostic for mapping and characterizing the fracture systems created and activated for reservoir development. The former need involves a local array with surface and shallow borehole receivers capable of minimum magnitude of complete recording, M_{comp}, equal to magnitude 1.0, preferably M_{comp} of 0.0. The stimulation monitoring need is achieved with deep-borehole, multi-level, high-temperature receiver systems. Both monitoring systems will provide continuous coverage through all field activities, including before, during, and after all injection operations and flow testing.

2. Monitoring for Mitigating Potential Seismic Hazard

The Utah FORGE site is located in rural Beaver County, Utah, approximately 16 km northeast from the town of Milford (Figure 1). Here we present a brief history of the local and regional seismicity and the history of monitoring in the FORGE area. Then, we present our recent and planned improvements for seismic monitoring at FORGE.

2.1. A Brief history of seismicity at FORGE

The University of Utah Seismograph Stations (UUSS), a partner in the Utah FORGE team responsible for seismic monitoring, has been recording and analyzing seismicity throughout Utah and the surrounding region for over 50 years. UUSS is a core agency within the Utah Earthquake Program funded by the State of Utah for monitoring seismicity within the State. UUSS is also a funded Advanced National Seismic System (ANSS) network and is the authoritative agency for monitoring seismicity in the Utah region and Yellowstone National Park.

Seismic activity in the area surrounding the Utah FORGE site has been steadily monitored by UUSS since 1981 (Pankow et al., 2019a) and event locations and magnitudes are captured in the UUSS catalog (Figure 1). Historical seismicity for the Utah region is compiled in a uniform moment magnitude catalog covering the entire state of Utah (1850–September 2012; Arabasz et al., 2015, 2017). The addition of a local FORGE seismic network in November 2016 improved detection sensitivity and magnitude of completeness estimates for the FORGE area (Figure 2). Seismicity near the Utah FORGE site is characterized by low-magnitudes ($M < 2.5$) occurring at low rates (on average ~5 earthquakes/year with the regional seismic network and ~170 earthquakes/year with the Utah FORGE network). Only 10 earthquakes with $M > 2.5$, the largest being M 3.8, occurred in the almost 40 years between 1981 and 2020. No naturally occurring seismic events have located within the FORGE footprint.

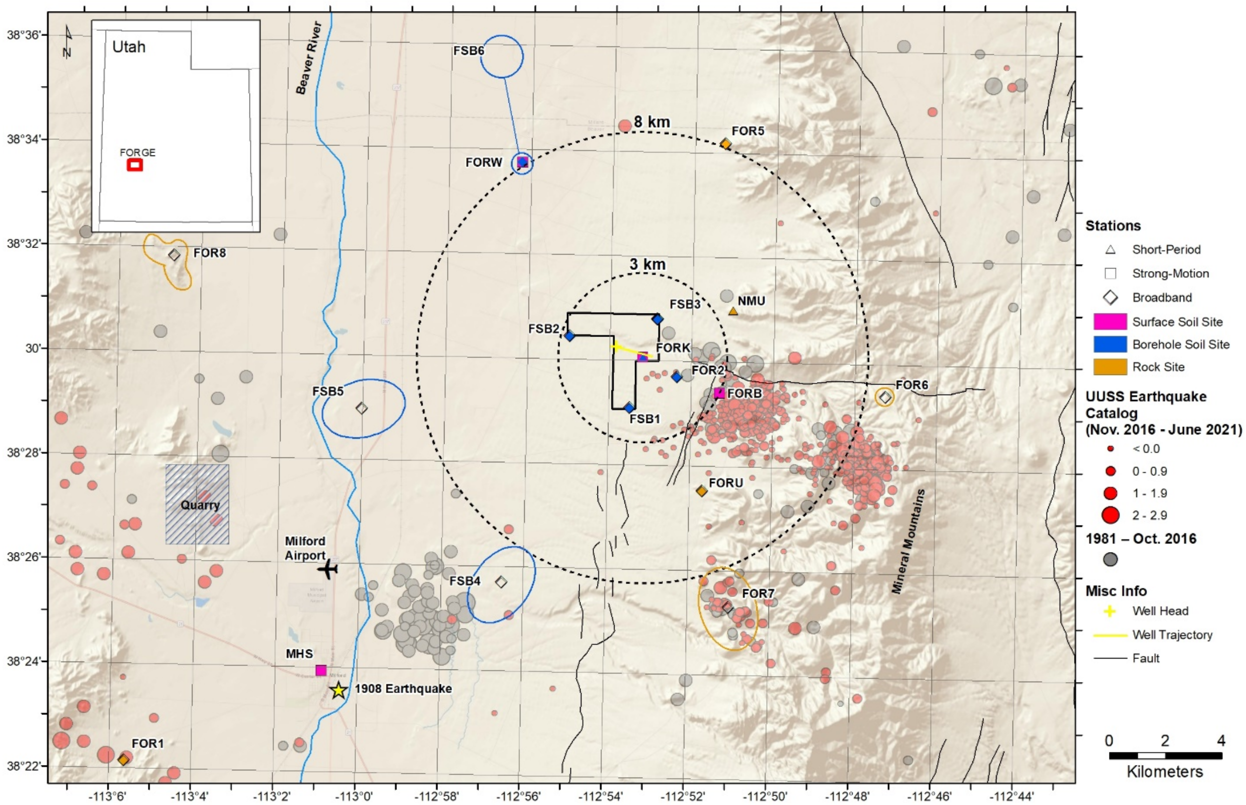

Figure 1: The location of the Utah FORGE study area is shown as the red box in inset upper left corner. The black polygon of the main figure shows the FORGE footprint. Gray circles (size scaled by magnitude), earthquakes (1981-2016) from UUSS catalog. Red circles (size scaled by magnitude), earthquakes (November 2016 – June 2021) from UUSS catalog. Yellow star, location of 1908 M 4.05 Milford earthquake. Dotted circles, 3- and 8-km radius rings from borehole 58-32 used to guide siting of seismic stations. Filled seismic stations, installed as of July 2021. Open symbols with ellipsoids, general location of stations to be installed before September 2021. Station MHS is located at Milford High School, indicating location of town. Black lines, local mapped faults. Quarry, airport, and Mineral Mountains indicate seismic cluster locations.

From the Arabasz et al. (2015) catalog of tectonic earthquakes, the largest event in the study area (M_W 4.05) occurred in 1908 and was located near the town of Milford (Figure 1). The closest significant earthquake (M > 6) occurred in 1901 in the Tushar Mountains ~50 km to the northeast of the Utah FORGE site. The largest recent tectonic event in the general vicinity to Utah FORGE was the January 2020 M_L 3.9 earthquake that occurred under the Mineral Mountains 12 km southeast of Milford (outside of the Utah FORGE study area).

There are three distinct areas of active seismicity in the vicinity of Utah FORGE (Pankow et al., 2017): (1) the Quarry area, approximately 15 km to the west, (2) the Milford Airport, approximately 10 km southwest, and (3) the Mineral Mountains less than 5 km east-south-east (Figure 1). Seismicity from the Quarry area is interpreted to be quarry blasts, not tectonic earthquakes based on proximity to known quarries, their small magnitudes (M 0.49 to 2.05), shallow depths, restricted timing (all events occur during daylight hours), and highly correlated waveforms implying repetitive source locations and mechanisms. The Milford airport cluster is near the M_W 4.05 1908 Milford earthquake (Figure 1). The recent events from this cluster have magnitudes ranging from M 0.46 to 3.91, and occur with random timing throughout the day and night. This cluster is interpreted as tectonic in origin. The Mineral Mountains seismicity locates mostly east of the Blundell Power Plant (station FORB, Figure 1) with a second, more dispersed subcluster south of station FORU (Figure 1).

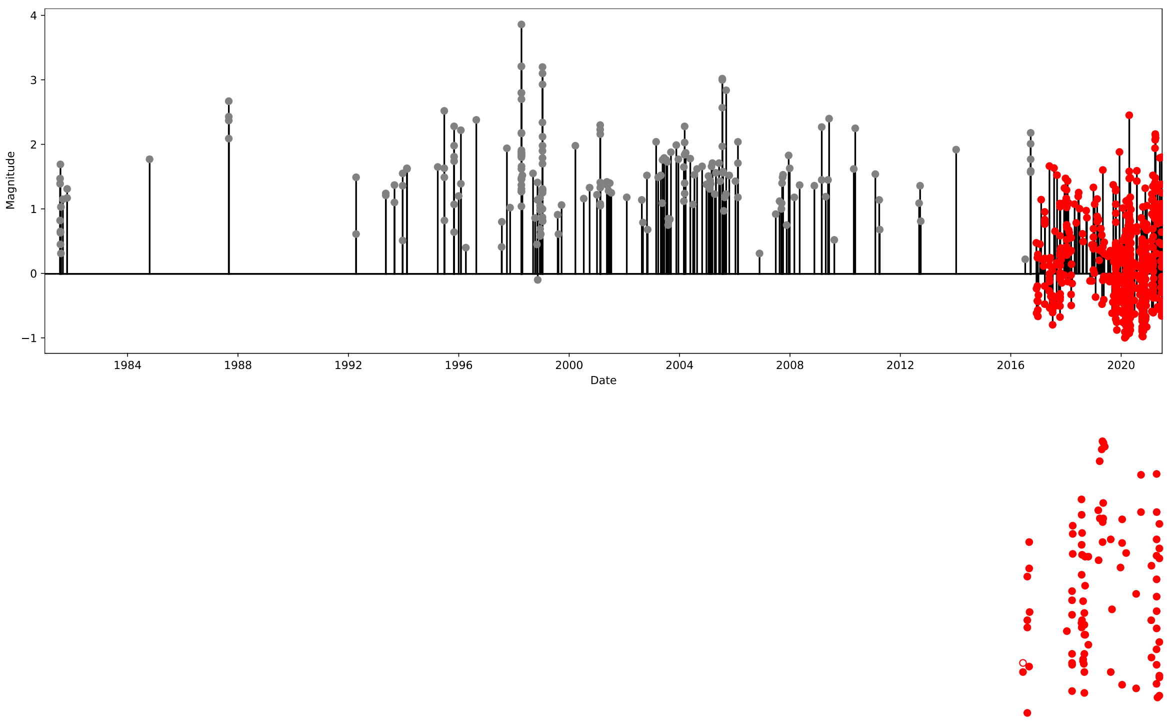

Figure 2: Magnitude time history for earthquakes occurring in the Utah FORGE region (Figure 1). Grey circles, earthquakes from the UUSS catalog 1981–2016. Red circles, earthquakes located after installation of the local Utah FORGE network. Top, 1981 through June 2021. Bottom, November 2016 through June 2021.

The densest cluster of seismicity in the Mineral Mountains area, the cluster east of the Blundell Power Plant, is a region characterized by repeating swarms (Zandt et al., 1982; Pankow et al., 2019b; Mesimeri et al., 2021). While focal depth is not well-constrained the depth of the swarm events tends to be > 5 km. Focal mechanisms indicate rupture on both east-west trending and north-south trending faults (Zandt et al., 1982; Mesimeri et al. 2021). The swarm activity does not correlate with injection at the Blundell Power Plant (Mesimeri et al., 2021).

In summary, based on the multiple-levels of seismic monitoring: (1) no naturally occurring seismic events locate within the Utah FORGE footprint; (2) natural seismicity over the Utah FORGE region occurs at low rates and with low magnitudes, typically M < 1.5; and (3) most seismic events in this area occur under the Mineral Mountains.

2.2. Improvement of earthquake monitoring at FORGE

For monitoring of potential seismic hazards, the goal is to achieve a magnitude-of-completeness of M 0 with detection capabilities down to M -1.5. In November 2016 a five-station temporary broadband surface seismic network was installed to ensure detection down to magnitude 0 (Pankow et al., 2019b). This surface network was capable of detecting and locating events down to M -1 in the Mineral Mountains 10 km east of Utah FORGE. Recently, the seismic network has been modified. Ongoing and planned improvements include installation of three 3-component broadband and three component accelerometers placed in shallow boreholes (~100 ft), three 3-component posthole broadband sensors (~150 ft), and five seismometers at rock outcrop sites within the Mineral Mountains (FSB and FOR stations, Figure 1). These sensors form two concentric rings centered over the planned reservoir stimulation area. The final configuration is designed to increase coverage and sensitivity to allow: (1) tracking changes in earthquake statistics; (2) tracking event migration within and outside the FORGE footprint; (3) improved hypocenter accuracy within the FORGE footprint; and (4) the analysis of source properties for the larger events.

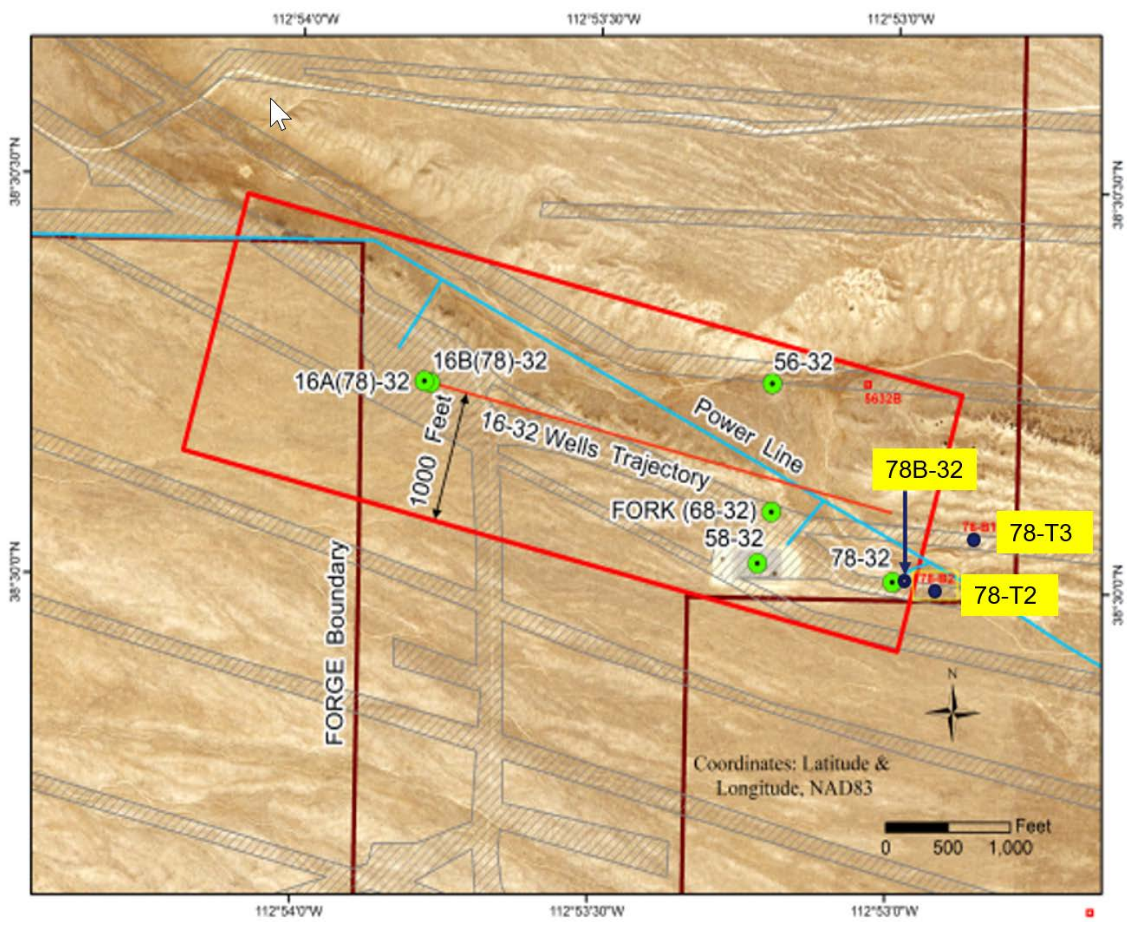

Figure 3: Plan view of Utah FORGE deep wells.

3. Deep Downhole Monitoring for Reservoir Development and Characterization

The surface and near-surface array described above is designed to detect and locate natural and induced seismicity over the entire Utah FORGE footprint for the purpose of hazard mitigation. An array of deep borehole sensors will also be deployed to detect very small microseismic events (-2.5 < M < -0.5) for the purpose of mapping the stimulated fracture volumes during and after injection stimulation operations. This will be accomplished initially with three deep monitor wells surrounding the toe-ward section of the injection well. During stimulation, high-temperature, digital, eight-level receiver strings will be deployed at or near reservoir depths. After injection, the digital strings will be replaced with retrievable, high-temperature analog receivers for continuous long-term monitoring of reservoir microseismicity.

3.1. Pilot downhole monitoring

A sequence of pilot injection tests was conducted in well 58-32 during April and May, 2019. These injection tests also provided an opportunity to place sensors in well 78-32, drilled to a TD of 3280 ft to test for the sensitivity of detecting microseismicity with sensors placed just below the top of granite (2650 ft) and up through the overlying basin fill (Figure 3). An 1100-ft long, 12-level digital receiver was placed with the lower 6 receivers below top of granite. In addition, a DAS fiber optic cable was cemented outside casing from TD to surface. Injection depth in 58-32 was approximately 7000 ft, over 4430 ft beneath the mid-string depth, providing a measure of detection sensitivity for small events. In total, 424 events were detected on the digital string with a magnitude range of $-2 < M_w < -0.5$ at distances of 3600 to 5200 ft. Injection rates were up to 650 gallon per minute for total volumes up to about 8200 gallons per injection phase. A few of the larger events were detected over the entire length of the DAS cable reaching to the near surface as well as on a subset of high-density surface stations that were temporarily deployed over the FORGE footprint.

3.2. Planning for the deep-well microseismic monitoring

The placement of the three deep monitoring wells in plan view form a triangle to focus event detection and location accuracy for stimulation injections to be initially conducted over the toe-ward section of well 16A(78)-32 (hereafter referred to as 16A). These are wells 58-32, 56-32 and 78B-32. Well 58-32 was drilled first and used for pilot injection tests at reservoir depths and now provides access for deep seismic receivers. Within permitted options for drilling, placements of 56-32 and 78B-32 were evaluated based on modeling various three-well array configurations, and selected for optimizing source location accuracy and detection sensitivity (e.g., Figures 3 and 4).

Location accuracies were computed using the method presented in Dyer et al. (2010). The computed errors for any given source location can be expressed as an error ellipsoid. The shape and orientations of the ellipsoids depends primarily on the combination of the arrival time data, the azimuthal or hodogram data, and the source-receiver geometries corresponding to each trial location in the model. Figure 5 shows the maximum errors in map and depth views for the case of three receiver strings placed deep within or near reservoir depths. Maximum error is the half-length of the error ellipsoid’s principal axis. The horizontal slice (map view, Figure 5) is at a depth of 8500 feet corresponding to the toe of 16A. The vertical slice (depth view, Figure 5) corresponds to an east-west plane going through the toe of 16A (at north -1000 ft). The model parameters are summarized in Table 1.

Relative source locations (resolution) can be further improved through consistent picking and waveform correlations. The receiver configuration shown in Figure 5 is designed to resolve fracture orientations, fracture height growth and zonal isolation or interactions for a series of stimulations along the 16A lateral. For example, along most of the length of 16A, location uncertainties are of order 50 feet. If the strings instead are located at the shallower depth levels considered in Figure 4, the location uncertainties increase to of order 100 feet (not plotted).

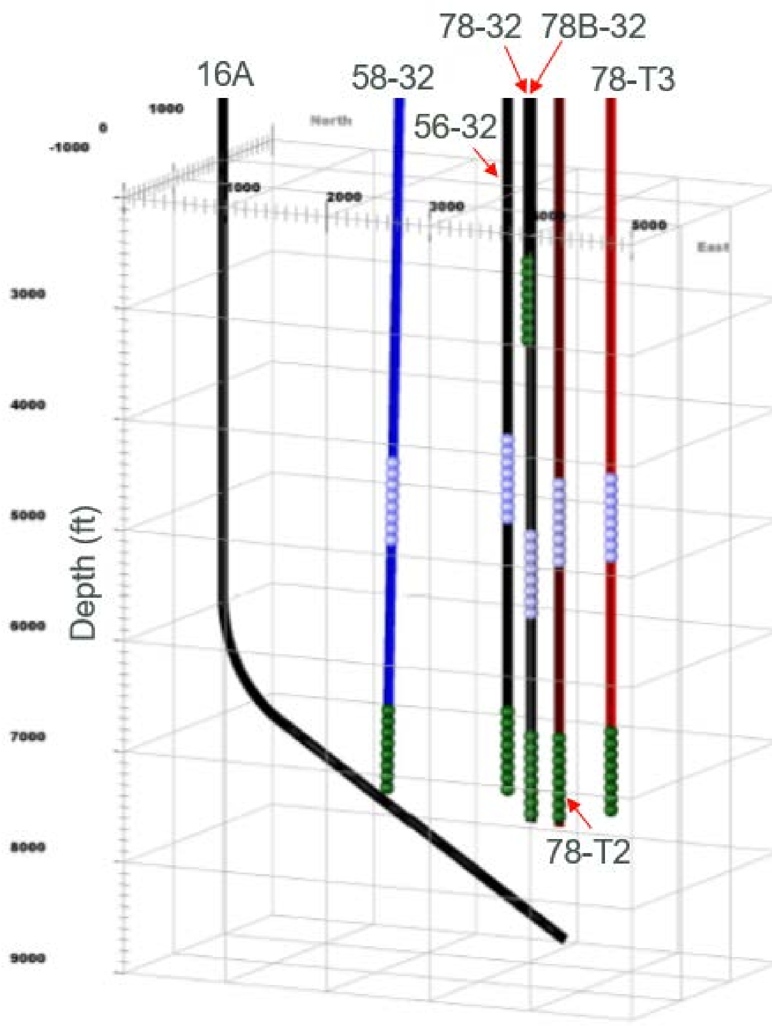

Figure 4: Perspective view of the wells considered in the seismic modeling. In this example three well locations for a deep well supplementing 58-32, 56-32 and 78-32 were evaluated; 78B-32, 78-T2, and 78-T2. Two depth positions for receiver strings were also considered, shallow (light blue) and deep (dark green), which requires higher temperature tool specifications (~200°C). 78B-32 would be a re-drill on the existing 78-32 well pad, shown offset 30 ft east of 78-32 (TD 3280 ft) (see Figure 3).

Using the method of Freudenreich et al. (2012), an analysis was also conducted to compute the minimum detectable magnitudes for selected receiver positions. The S wave was used in this analysis as for real data it has better signal to noise than the P wave and so may be expected to provide more reliable magnitudes. A seismic Q of 350 was derived by matching modelled sensitivities with the distribution of magnitudes of microseismicity observed in 78-32 during the pilot injection tests in 58-32. Similarly, an S-wave corner frequency of 120 Hz was assumed based on the mean corner frequency determined from 58-32 pilot microseismic data. For the deep receiver placement, detection thresholds over the toe target area of 16A are down to about Mw -2.2 to -2.3 for all receivers. (Figure 6).

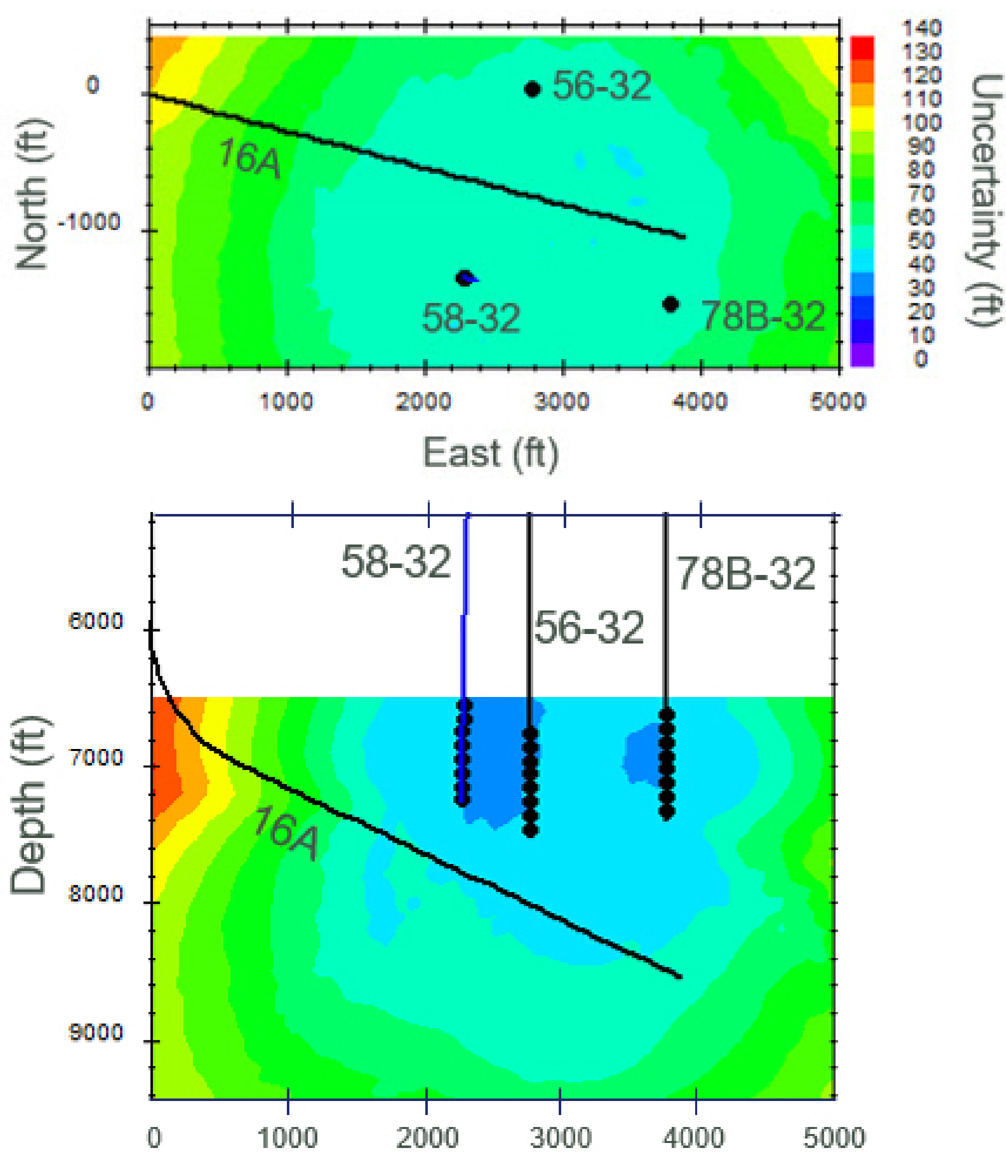

Figure 5: Map and depth views of computed maximum uncertainties. The horizontal slice (map view) is at a depth of 8500 feet corresponding to the toe of 16A. The vertical slice (depth view) corresponds to an east-west plane going through the toe of 16A (at north -1000 ft).

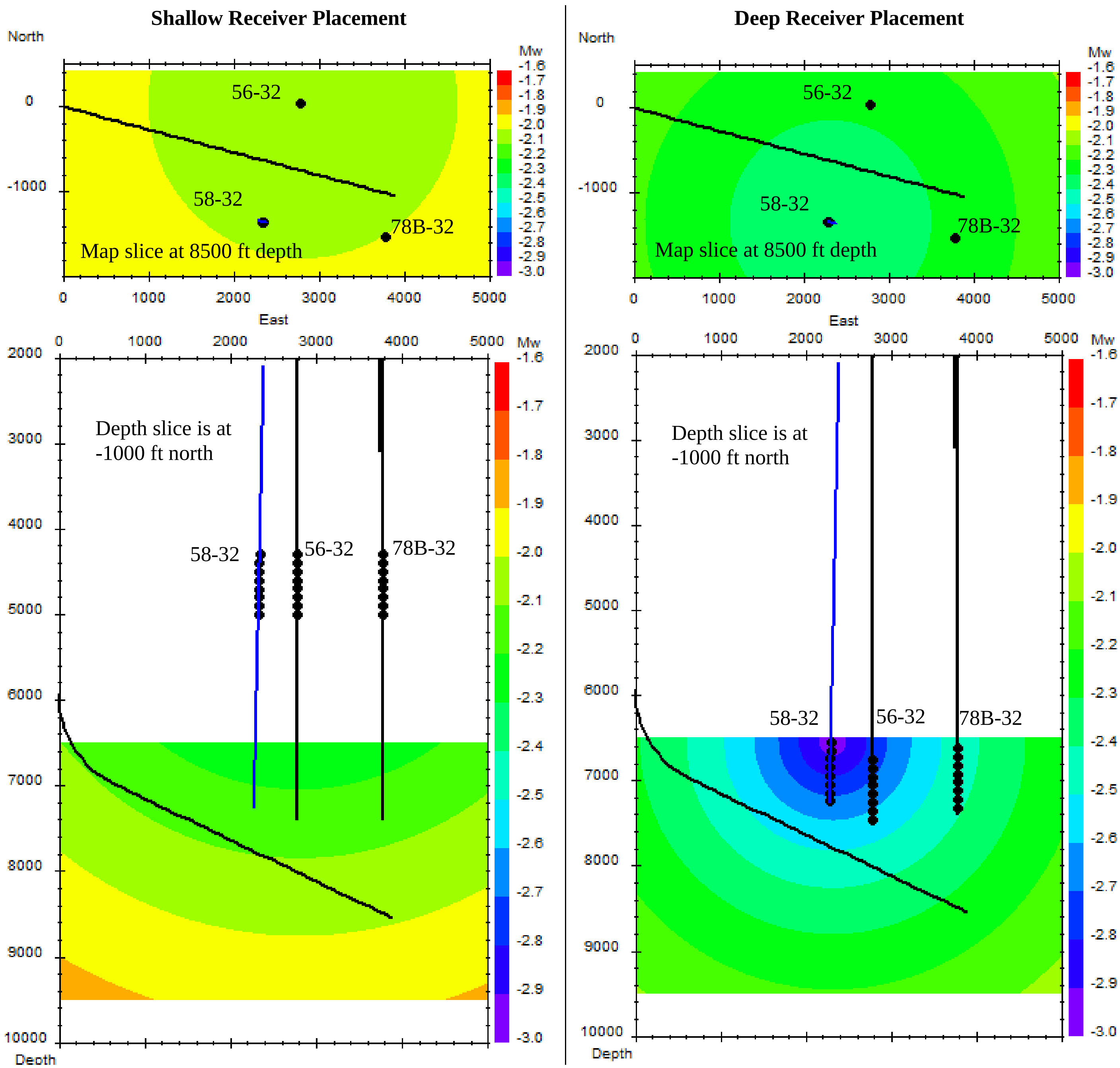

Figure 6: Map and depth views of computed moment magnitudes (Mw) detection sensitivities for shallow placement of receiver strings (left) and deep placement of receiver strings (right). For shallow receiver configuration sensitivity is computed at the shallowest receiver of 56-32 (4300 ft depth). For the deep receiver configuration sensitivity is computed at the shallowest receiver of 58-32 (6800 ft depth). The detection is for the S-wave assuming a signal-to-noise ratio of 3 and an RMS background noise level 0.01 micron/sec.

Table 1: Model and data parameters for estimating source location uncertainties

Model	
Vp 19,000 ft/sec, constant	average in granite from sonic logs
Vs 11,000 ft/sec, constant	average in granite from sonic logs
Data Accuracies	
P-picks ± 1 ms	
S picks ± 2 ms	
Hodogram ±5°	
Data Used	
P and S picks for all groups (24 three-component receivers, 8 per well)	
Hodograms for 58-32 and 56-32 receivers and 78B-32	

The reservoir-level seismicity monitoring plan is to deploy high-temperature (210°C) digital strings close to the deep settings illustrated in Figures 4, 5 and 6 allowing source coverage and sensitivity for good location accuracy and source mechanism resolution. The three digital receiver strings will be deployed only for the injection stimulation operations. Immediately following the stimulation operations, each digital string will be pulled and replaced with 2-level, 3-component, high-temperature (up to 260°C), retrievable, analog receivers to be used for continuous, long-term downhole detection and analysis of reservoir microseismicity. The actual temperature of deployment will be limited to 246°C due to the wireline's temperature specifications.
Supplementing the three deep-well receiver strings will be use of permanent DAS fiber-optic cables outside of casings in 78-32 (surface to TD 3280 ft) and 78B-32 (planned to be from surface to casing-shoe depth of 8500 ft). In addition, a prototype three-level, 3-component fiber-optic seismic receiver string will be deployed in well 78-32 (TD 3280 ft) during the 16A stimulation operations. These additional receiver systems will provide direct comparison with the more conventional digital borehole receiver strings for testing and evaluating their performance in an active geothermal environment.

4. Summary

The Utah FORGE seismic monitoring plan provides infrastructure for two purposes: first, to continuously monitor seismicity as a part of mitigation strategies for potential seismic hazards associated with fluid injection and migration over the larger FORGE footprint, and second, to monitor during stimulation or injection operations as a diagnostic for mapping and characterizing the fracture systems created and activated for reservoir development. The former need involves an array of surface and shallow borehole receivers. The latter need is achieved with deep-borehole, multi-level, high-temperature receiver systems. Both monitoring systems will provide continuous coverage through all field activities, including before, during, and after all injection operations and flow testing.

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