THE UTAH FRONTIER OBSERVATORY FOR GEOTHERMAL RESEARCH (FORGE): A LABORATORY FOR EGS DEVELOPMENT

Joe Moore[1], Rick Allis[2], Kristine Pankow[3], Stuart Simmons[1], John McLennan[1], Philip Wannamaker[1], William Rickard[4], Robert Podgorney[5]

[1]Energy and Geoscience Institute, University of Utah, Salt Lake City, Utah

[2] Utah Geological Survey, Salt Lake City, Utah

[3]University of Utah Seismograph Stations, University of Utah, UT 84112

[4] Geothermal Research Group, Palm Desert, California

[5]Idaho National Laboratory, Idaho Falls, Idaho

jmoore@egi.utah.edu

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ABSTRACT

The U.S. Department of Energy is sponsoring the FORGE (Frontier Observatory for Research in Geothermal Energy) initiative to bring Enhanced Geothermal System (EGS) development to commercial viability and visibility. The project will create a controlled environment where EGS technologies can be developed and tested.

The Utah FORGE site, one of two sites being considered, is located in central Utah, 350 km south of Salt Lake City. Since the 1970s, more than 100 wells, the deepest to 3.8 km, have been drilled in the vicinity of the site. Well logs, detailed geologic mapping, geophysical surveys and seismic data provide information on temperatures, thermal gradients, rock types, and in-situ stresses. High angle, northeast-trending faults that formed during east-west extension offset the alluvium and recent sinter deposits but these do not extend into the FORGE site. Thirty years of monitoring indicates that natural seismicity surrounding the FORGE site is low. The data indicate the site is underlain by large volumes of Tertiary granite and Precambrian gneiss with temperatures from 175–225°C at depths of 2 to 4 km. Fault orientations, borehole breakouts, and earthquake solutions indicate the maximum horizontal stress is NNE-SSW.

The project is being conducted in multiple phases. Phases 1 and 2A included project planning and review of potential environmental and cultural constraints. None that could adversely affect the project were identified. Phase 2B includes drilling a 2.1 km deep well to determine in-situ stresses, permeability, lithology and temperature within the thermal reservoir. Preliminary results from this well will be presented. At the conclusion of Phase 2B, a final site for the FORGE laboratory will be selected. In subsequent phases, the supporting infrastructure will be built and wells for injection and production will be drilled, stimulated and tested.

1. INTRODUCTION

The first Enhanced Geothermal Systems (EGS) demonstrations were conducted at Fenton Hill, New Mexico in the late 1970s and early 1980s. Although the Fenton Hill project demonstrated the potential of EGS development, no EGS project has yet reached large-scale commercial levels of production. The goal of the U.S. Department of Energy's Frontier Observatory for Research in Geothermal Research (FORGE) program is to develop the techniques required for creating, sustaining and monitoring EGS reservoirs for commercial development.

The FORGE program consists of three phases. Phase 1 involved desktop studies of existing data at five sites. At the conclusion of Phase 1, two sites were selected, the University of Utah's Milford, Utah site and Sandia National Laboratories Fallon, Nevada site. During Phase 2, a 2134 m well MU-ESW1 will be drilled at the Utah FORGE site to obtain direct measurements on temperature, stress, rock type and permeability in the granitic reservoir rocks. Compliance with the National Environmental Policy Act will be demonstrated and a Seismic Hazard Program will be prepared. The U.S. DOE will select a final site for FORGE in mid-2018. Essential Phase 3 activities include the creation and monitoring of the EGS reservoir, characterization and modeling of the heat exchange potential of the reservoir through the stimulated fracture network, and monitoring of microseismicity. The ultimate goal of the FORGE project is to demonstrate to the public, stakeholders and the energy industry that EGS technologies have the potential to contribute significantly to power generation in the future.

2. THE UTAH FORGE SITE

The Utah FORGE site is located 350 km south of Salt Lake City and 16 km north of Milford, a small community with a population of 1400 (Fig. 1). 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 are located approximately the same distance south of Milford.

Considerable supporting infrastructure exists near the site. Milford has motel accommodations, a supermarket, hardware store, and a hospital. Beaver, a larger population center, is located 56 km from Milford adjacent to I-15, a major interstate. The Union Pacific Railroad passes through Milford, offering the possibility of shipping heavy equipment by rail and then by truck to the FORGE site. The Milford Municipal Airport, located a few kilometers north of Milford, has a 1524 m long sealed runway that can accommodate piston or turboprop, single- or twin-engine planes.

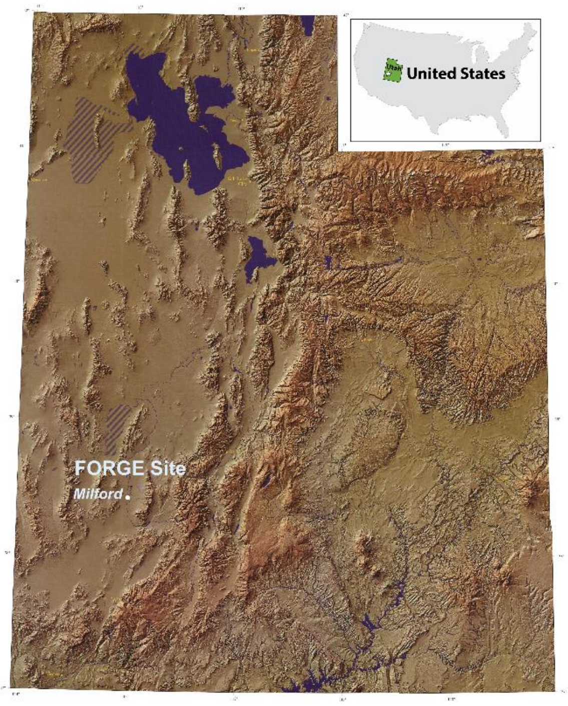

Figure 1: Location map.

The area around the FORGE site has been the focus of numerous geoscientific studies over the last 40 years, starting with intensive geothermal exploration during the late 1970s (Fig. 2). Geological mapping, gravity and magnetotelluric surveys, and the drilling, logging, and sampling of 80 shallow (<500 m) and 20 deep (> 500 m) wells, including Acord-1, a 3.8 km deep well in the middle of north Milford Valley, 3 km west of the FORGE drill site, were conducted. Wells 9-1 and 82-33 were drilled west and north of the Roosevelt Hot Springs geothermal system as part of the geothermal development program.

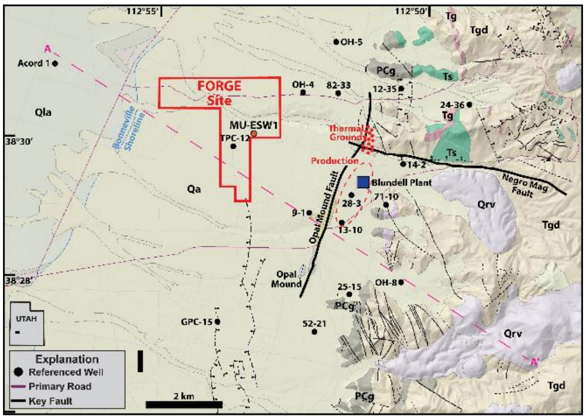

Figure 2: Geologic map of the FORGE site and surrounding area, Milford, Utah from Nielson et al., 1986. For clarity, only a few of the many wells are shown. Abbreviations for map units: Qa=Quaternary alluvium; Qrv=Quaternary rhyolite; Tgd=Tertiary granodiorite; Tg=Tertiary granite dike; Ts=Tertiary syenite; PCg=Precambrian gneiss.

The FORGE well site is situated centrally between these three, deep, non-productive wells, all of which display conductive thermal gradients and temperatures of more than 175°C at less than 3 km depth. The data from these wells demonstrate the FORGE site is outside the boundaries of any existing hydrothermal system and that the required reservoir criteria of temperature (175ºC-225ºC), rock type (crystalline rock) and depth (1.5-4 km) established by the U.S. DOE exist at the site. The availability of non-potable water, the lack of environmental issues, the local infrastructure, and the extensive suite of existing scientific and well data are additional supporting considerations.

3. GEOLOGY

The FORGE site is located on a gently sloping alluvial plane on the west flank of the Mineral Mountains. The geology of the Mineral Mountains east of the FORGE site is shown in Figure 2. Here the geology is composed of Precambrian gneiss, Tertiary plutons and Quaternary rhyolite (Kirby, et al., 2012). Isotopic dating indicates metamorphism of the Precambrian rocks occurred ~1720 Ma (Aleinikoff et al., 1987).

The Tertiary plutonic rocks include diorite, granodiorite, quartz monzonite, syenite, and granite. Their subsurface distributions are known primarily from detailed investigations of four wells, 14-2, 52-21, 9-1, and Acord-1 (Glen and Hulen, 1978; Glenn et al., 1980; Sweeny, 1980; Welsh, 1980; Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 1997; Hintze and Davis, 2003). U-Pb zircon dating indicates development of the plutonic complex that began with the emplacement of (hornblende) diorite at 25.4 Ma (Aleinikoff et al., 1987); younger plutonic rocks were emplaced at ~18 Ma and 11 to 8 Ma (Nielson et al., 1986; Coleman and Walker, 1992; Walker et al., 1997).

The youngest intrusions produced <1 Ma rhyolites that form domes along the crest of the range. Temperatures 250ºC in the Roosevelt Hot Springs reservoir and to the west in Acord-1 suggest the presence of a still cooling magma chamber in the shallow crust extending westward from the crest of the range.

The Tertiary and Quaternary basin fill in the Milford Valley consists dominantly of alluvial and lacustrine deposits that contain interbedded sand, silt, gravel, and clay (Hintze and Davis, 2003). In Acord-1, nearly 3 km of unconsolidated basin fill was encountered above the crystalline basement rocks (Fig. 2). Minor thicknesses of Tertiary ash-flow tuffs, probably Miocene in age, are present but have not been found in wells drilled at Roosevelt Hot Springs. At the FORGE site, the basin fill is 637 m thick.

Paleozoic and Mesozoic sedimentary sequences are exposed at the northern and southern parts of the Mineral Mountains. These sedimentary rocks are major components of the regional stratigraphy but were not encountered in any of the deep wells (Nielson et al., 1986).

4. STRUCTURAL RELATIONSHIPS

The structural setting of the FORGE site reflects the effects of two distinct tectonic events; late Mesozoic to early Cenozoic compression during the Sevier orogeny and middle Tertiary to Recent extension. The Sevier orogeny produced large-scale low-angle thrust faults found in the surrounding mountain ranges (e.g., Hintze and Davis, 2003), but the effects of this orogeny near the FORGE site are poorly understood.

The younger faulting episode is related to ongoing east-west Basin and Range extension, which dates back to at least ~17

Ma. This extension has produced predominantly north-south trending fault zones (e.g., Hintze and Davis, 2003; Dickinson, 2006). The most prominent of the Basin and Range structures shown in Figure 2 is the Opal Mound Fault), which dips steeply to the east and offsets surficial deposits of alluvium and silica sinter, with a total down-dip displacement of at least 15 m (Nielson et al., 1986). This fault separates the convective thermal regime of the Roosevelt Hot Springs geothermal system from the conductive thermal regime to the west, beneath the FORGE site.

South of the Opal Mound Fault, north-south trending faults form a series of short, narrow grabens and horsts (Nielson et al., 1986). These faults die out to the north as the FORGE site is approached.

The Negro Mag fault is another major steeply dipping fault, but it trends east-west (Fig. 2). The fault cuts across the Mineral Mountains for ~6 km, however the direction and amount of displacement are unknown due to the absence of markers within the plutonic rocks (Nielson et al., 1986). An east-west trending structure, 2 km south of Negro Mag fault, was the site of seismicity in the late 1970s (Zandt et al., 1982; Nielson et al., 1986). Both the Negro Mag and Opal Mound faults appear to terminate at their intersection. These east-west faults may reflect regional arc-parallel structures, formed as Eocene-Oligocene magmatism migrate southward migrating and/or Proterozoic structures in the deep-seated basement (e.g., Dickinson, 2006; Wannamaker et al., 2015).

The direction of S_{Hmax} in the vicinity of the Milford FORGE (Fig. 3) site is constrained by: 1) borehole breakouts in 52-21; 2) image logs in 14-2 (Keys, 1979); 3) the attitudes of joints and dikes (Yusas and Bruhn, 1979); and 4) focal mechanisms of seismic events; (e.g., Whidden and Pankow, 2012); These data all indicate a consistent maximum horizontal compressive stress, S_{Hmax}, primarily directed N-S (170-180°) to NNE-SSW (035°).

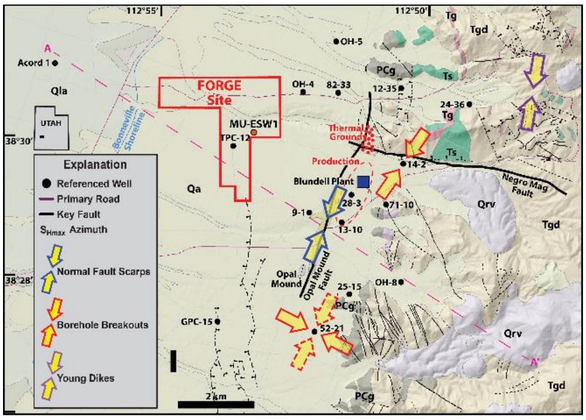

Figure 3. Summary of S_{Hmax} orientations based on normal fault scarps, borehole breakouts and young dikes. Stress data compiled by Davatzes (2016, written comm.)

Mechanical testing of core samples of Precambrian gneiss from 52-21 indicates the rock is very strong, with very low porosity and permeability. The compressive strength was measured at three separate confining pressures, 0, 2800, and 8000 psi, giving average values of 2.8x10^4, 6.0 x10^4, and 9.0 x10^4 psi, respectively. The porosity is 0.13% and the permeability was measured at 0.3 microdarcies. These data imply that permeability enhancement within the FORGE reservoir will rely on hydroshearing of existing fractures and not the creation of new fractures.

Detailed fracture mapping of the plutonic rocks in the Mineral Mountains has identified three fracture sets (Bartley, 2017, written comm.): steep E-W fractures; gently west dipping fractures; and steep N-NNE striking fractures. Direct information on the behavior of these fractures will be obtained after MU-ESW1 (Fig. 2) is completed and a minifrac is conducted in the reservoir rocks.

5. THERMAL STRUCTURE

More than 100 shallow and deep wells provide temperature data surrounding the FORGE site. Wells located between the central Milford Valley and the Opal Mound fault show that the heat flow ranges from 120 to 200 mW/m^2. In the vicinity of the FORGE site (e.g. TPC-12 in Fig. 4), the heat flow is in the range 180 ± 40 mW/m^2. To the east; in 9-1 and 82-33, the heat flows are significantly higher at depths less than about 500 m. However, temperatures in these wells at shallow depths are affected by outflow from the Roosevelt Hot Springs geothermal system. Although near-surface gradients exceed 150°C/km and heat flows range from 300 to >1000 mW/m^2, (for example, well RHS-335; Fig. 4). These temperature gradients cannot be extrapolated much below 500 m depth, and when RHS-335 is compared to 9-1, the gradients are clearly decreasing with increasing depth (Fig. 4).

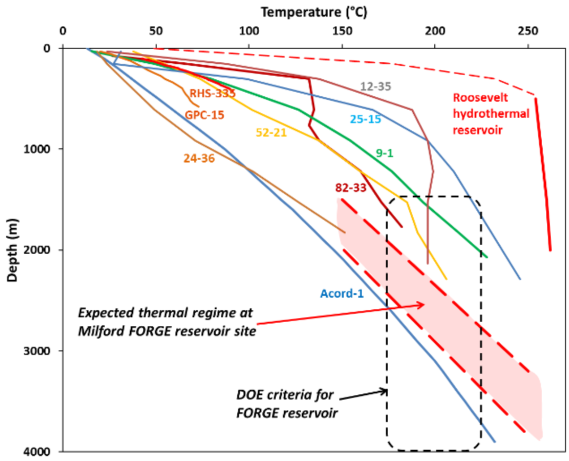

Figure 4. Temperature and pressure profiles in wells surrounding the FORGE site. The dashed rectangle shows conditions required by the U.S. DOE. See Figure 2 for well locations. Productive wells tapping the Roosevelt Hot Springs geothermal system display convective thermal gradients. These wells lie east of the Opal Mound fault. The three deep wells surrounding the FORGE site, Acord-1, 82-33 and 9-1, display conductive gradients

East of the Opal Mound fault, many of the shallow temperature profiles exhibit boiling-point-for- depth profiles, indicative of hydrothermal upflow. Here, in contrast to the conductive thermal gradients west of the Opal Mound fault, the thermal gradients are convective and the temperature profiles are controlled by steam-water saturation conditions and hydrostatic pressure gradients.

Integration of all temperature gradient data shows that a large area of anomalously high conductive heat flow, covering about 100 km^2, surrounds the FORGE site (Fig. 5). The total volume of crystalline basement rock having temperatures

>175ºC down to 4 km depth is more than 100 km^3. The Opal Mound fault forms the eastern boundary this thermal regime and, as discussed below, marks the transition to the Roosevelt Hot Springs where convective heat flow prevails and covers a much smaller area of ~10 km^2.

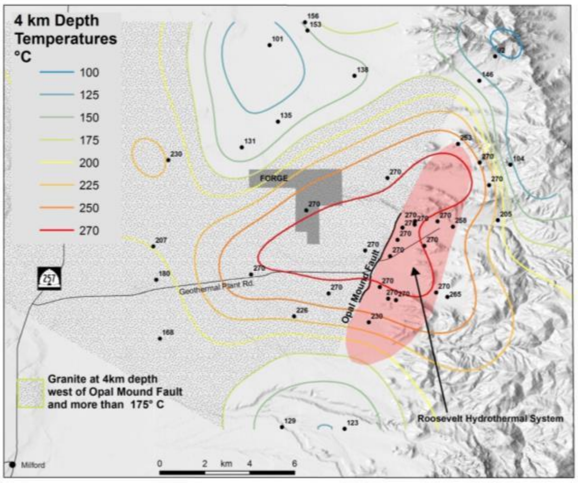

Figure 5. Contours of temperature at 4 km depth derived from observations in the deep wells and geotherms fitted to thermal gradient wells. The stipple area indicates where the granite is hotter than the minimum reservoir temperature of 175°C. The red shading shows the extent of the Roosevelt Hot Springs geothermal system.

Prior to the start of production at Roosevelt Hot Springs in 1984, deep wells east of the Opal Mound fault had a uniform pressure profile consistent with hot water having a density of 800 kg/m^3 (Allis and Larsen, 2012; Fig. 6). The one deep well west of the Opal Mound fault, 82-33, had a pressure profile consistent with cold water with a density of 1000 kg/m^3, about 30 bars lower than wells on the east side of the Opal Mound fault in the Roosevelt Hot Springs geothermal system (Faulder, 1994). Other wells west of the Opal Mound fault plot on the same pressure gradient as 82-33. These well data indicate the existence of a major pressure boundary, which coincides with the Opal Mound fault. Well 9-1 is located on that boundary and is unproductive, and it is used as a monitoring well. These data imply the presence of two distinct pressure regimes across the Opal Mound fault (Allis et al., 2016). The FORGE site lies to the west of this barrier. At a depth of 2.5 km depth, the pressure within the FORGE reservoir is expected be at 228 bars (3300 psi).

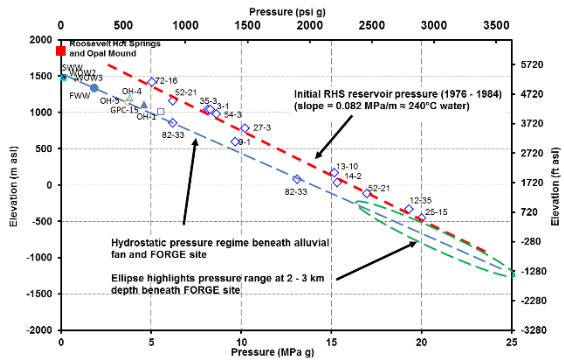

Figure. 6. Pressure profiles in wells surrounding the FORGE site. Wells within the Roosevelt Hot Springs geothermal system display a hydrostatic pressure head that is 30 bars higher than wells on the west side of the Opal Mound fault.

6. GEOMETRY OF THE BASEMENT ROCKS

Gravity and well data constrain the depth to the crystalline rocks west of the Mineral Mountains (Fig. 7). The central part of the Milford Basin, beneath Acord-1, is steep walled and V-shaped. The basin axis is oriented north-south, perpendicular to Basin and Range extension. Outward and upward, the basement contact flattens to form a gently dipping surface that extends beneath the FORGE site, where the depth to the crystalline basement ranges from over 1000 m on the western side to about 600 m on the eastern side. Buried faults near the deepest part of the basin are inferred from the gravity profile and westward thickening of the basin fill (Allis et al., 2016; Hardwick et al., 2016).

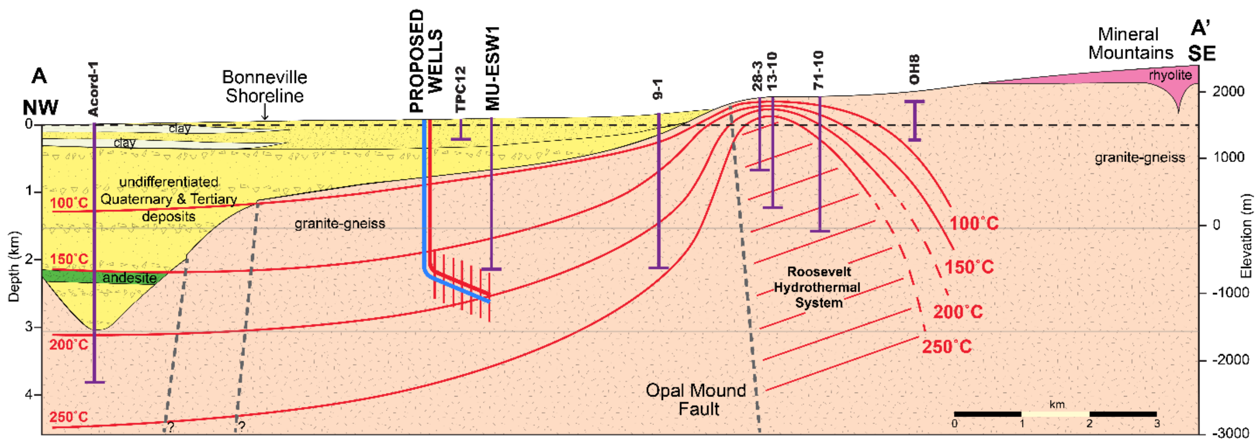

Figure 7. Cross section A-A' from Figure 2, showing the top of the crystalline basement rocks in the Milford Basin in the vicinity of the FORGE site. Precambrian gneiss and Tertiary plutonic rocks are undifferentiated. The Roosevelt Hot Springs hydrothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements. The figure shows the proposed FORGE injection and production wells and the vertical 2134 m deep test well currently being drilled.

7. MICROSEISMICITY

Seismicity has been monitored in the area around the FORGE site since 1981 by the University of Utah Seismograph Stations (UUSS) (Pankow et al., 2017). Analysis of the UUSS catalog shows that seismic events near the Utah FORGE site tend to cluster in three areas; one near Milford, the second 10 km northwest of Milford and the third northeast of Milford, east and southeast of the FORGE site (Fig. 8). The events northwest of Milford occur only during daylight hours and are characterized by small magnitudes (M=0.49 to 2.05), shallow depths (above 2.5 km below sea level), and highly correlated waveforms implying a similar location and source mechanism. These events are interpreted as the result of quarry blasts, not tectonic earthquakes (box labeled Quarry; Fig.8).

Seismic events located near Milford (box labeled Airport, Fig. 8) are not far from a 1908 M=4.1 event. The magnitudes of these tectonic events range from 0.46 to 3.87. Based on the moment tensor from an M=3.8 earthquake (depth 6 km), the direction of minimum horizontal stress (T-axis, or S_{Hmin}) is NW-SE (Whidden and Pankow, 2012), close to the extension direction inferred for the Milford Basin although the focal mechanism for this event is strike-slip.

Northeast of Milford, seismicity occurs primarily within the box labeled Mineral Mountains (Fig. 8) east of the FORGE site. In November, 2016, the seismic network was upgraded with the installation of five broadband seismometers in order to monitor seismicity under the FORGE site. These seismometers allow detection of seismic events with magnitudes <0. Significantly, no evidence of seismic activity under the Utah FORGE site has been detected by the newly installed network.

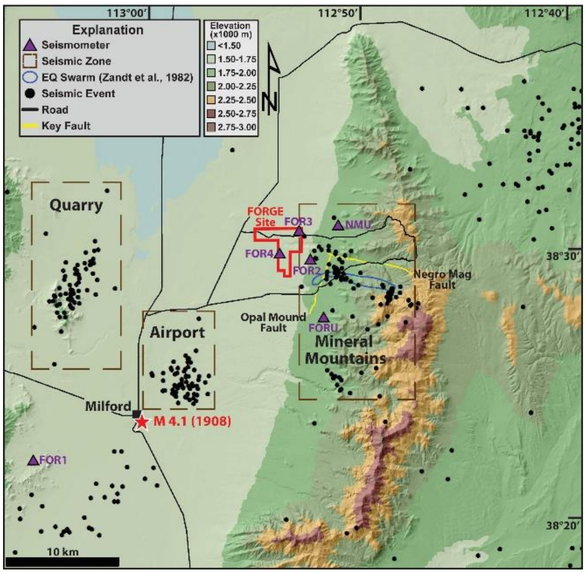

Figure 8. Locations of seismic events in the region surrounding the FORGE site (red outline) (Pankow et al., 2017). Black circles are seismic events occurring between 1981- 2016. The red star marks the location of the 1908 M 4.1 Milford earthquake. Brown dashed boxes show the locations of seismic source zones. The black square near the 1908 seismic event is the town of Milford. Purple triangles are seismic stations. The Opal Mound and Negro Mag faults are shown in yellow. The blue polygon is the area of the earthquake swarm defined by Zandt et al. (1982).

Faults within the alluvium provide a record of seismicity during Quaternary time. Faults are present in the alluvium south of the FORGE site but do not continue northward into the site. Although the deposits have not been dated directly, the least dissected alluvium within the FORGE site is cut by the Pleistocene Lake Bonneville shoreline. This suggests the deposits are more than ~18,000 years old (Kleber et al., 2017).

Potter et al., (2017) examined the relationship between microseismicity and injection at the nearby Blundell geothermal power plant but found none (Fig. 9). The lack of any correlation with injection suggests injection at the FORGE site, into the same reservoir rocks, will not lead to significant induced seismicity.

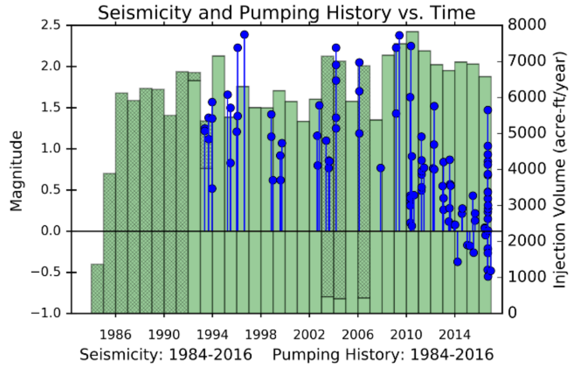

Figure 9. Time-magnitude histories of seismic events, shown as blue circles, located northeast of Milford and east of the FORGE site. No seismic events have been located within the FORGE footprint. Green bars represent the Blundell power plant injection history; cross hatched regions calculated based on the plants power production. No visible correlation is apparent between the seismic events and the volume of fluids injected.

8. CONCLUSION

The Milford FORGE site is ideally suited for the development and testing of technologies that can be used to create and sustain EGS reservoirs. The FORGE reservoir will be developed in weakly altered Tertiary granite and Precambrian gneiss at a depth below about 1980 m. The geology and thermal structure of the region surrounding the site is well characterized as a result of geological mapping, geophysical surveys and the drilling, logging, and sampling of nearly 100 wells, since the 1970s. Additional direct information on rock types, fracture abundances and orientations, temperature, permeability, and stress characteristics at the site will be obtained from measurements in a 2134 m vertical well currently being drilled.

The FORGE site is separated from the nearby Roosevelt Hot Springs geothermal system by the north-south trending Opal Mound fault that has formed in response to ongoing east-west Basin and Range extension. Temperatures within the geothermal system are close to 250°C. Convective thermal gradients characterize wells east of the Opal Mound fault whereas conductive thermal gradients characterize wells surrounding the FORGE site west of the Opal Mound fault.

Pre-production pressure profiles of deep wells in the geothermal system display a hydrostatic pressure head that is 30 bars higher than wells on the west side of the Opal Mound fault. This pressure difference requires the presence of two distinct pressure regimes, with high-permeability rock associated with the hydrothermal system to the east, and relatively impermeable rock to the west beneath the FORGE site.

The existing geoscientific data demonstrate the FORGE site is outside the boundaries of any existing hydrothermal system and that the required reservoir criteria of temperature (175º-225ºC), rock type (crystalline rock) and depth (1.5-4 km) established by the U.S. DOE for EGS development exist at the site. The low risk of seismic activity and impact to the environment, a well-developed local infrastructure, the absence of potable groundwater, endangered fauna or flora and a welcoming community, are additional positive attributes of the site.

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