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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): An International Laboratory for Enhanced Geothermal System Technology Development

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ABSTRACT

In 2018, the US Department of Energy selected a location near Milford, Utah as the site for its Frontier Observatory for Research in Geothermal Energy (FORGE). The project will provide a controlled environment where technologies for characterizing, creating and sustaining EGS reservoirs can be developed and tested.

Numerous geoscientific studies have been conducted in the region since the 1970s in support of geothermal development at Roosevelt Hot Springs. In 2017, well 58-32 was drilled to a measured depth of 2297 m (7536 ft) on the FORGE site to characterize the reservoir rocks and thermal regime. New geologic mapping, integrated with 3-D seismic reflection, gravity, hydrologic and soil gas surveys, has provided additional information on the region. Well 58-32 penetrated 1323 m (4340 ft) of Tertiary plutonic rocks dominated by granite and quartz monzonite below 968 m (3176 ft) of alluvial deposits. The well encountered a conductive thermal regime and a bottom hole temperature of 199°C (390°F). More than 2000 natural fractures were identified, but measured permeabilities are low, less than 30 microdarcies. Induced fractures indicate the maximum horizontal stress trends NNE-SSW, consistent with geologic and well observations from the surrounding area. Approximately 46 m (150 ft) at the base of the well was left uncased for stimulation testing. During the testing, a maximum wellhead pressure of ~27.6 MPa (4000 psig) and an injection rate of 22 l/s (8.7 bpm) was reached. Stress gradients ranged from 14.0 kPa/m (0.62 psi/ft) for σ_{Hmin} to 17.4 kPa/m (0.77 psi/ft) for σ_{Hmax}. A gradient of 25.6 kPa/m (1.13psi/ft) was calculated for σ_V. Despite the low stimulation pressures and injection rates, enhancement of the induced fractures is clearly apparent when pre- and post-injection Formation MicroImager (FMI) logs are compared. These changes demonstrate the suitability of the FORGE reservoir rocks for EGS development.

The FORGE site has been seismically quiescent since monitoring began in the 1980s. Analysis of seismic data and regional fault characteristics confirm minimal seismic hazards and low risk of induced seismicity.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) offer the potential to bring low-cost geothermal energy to locations that lack natural permeability. Since the late 1970s, close to a dozen EGS demonstration projects have been conducted. The results have been disappointing and none of the projects have achieved large-scale commercial levels of production. The goal of the U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE) program is to develop the techniques required for creating, sustaining and monitoring EGS reservoirs. 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 future power generation.

In 2018, the Department of Energy (DOE) selected a site in south-central Utah for the FORGE laboratory (Figure 1). The area around the FORGE site has been the focus of numerous geoscientific studies over the last 40 years. More than 80 shallow (<500 m) and 20 deep (>500 m) wells were drilled and logged, providing a very complete picture of the thermal structure of the region (Figure 2). The deepest well, Acord-1, reached a depth of 3.8 km (12,650 ft) (Welsh, 1980). Recent geological mapping, 3-D seismic reflection, gravity and geochemical surveys, and the drilling, logging and testing of well 58-32 have added significantly to our understanding of the FORGE site (Allis et al., 2018; Gwynn et al., 2018; Hardwick et al., 2018; Jones et al., 2018; Kirby et al., 2018a, b; Miller et al., 2018).

In this paper we summarize recent contributions to our understanding of the FORGE site and their implications.

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 (refer to Figure 1). The FORGE footprint covers an area of about 5 km^2 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.

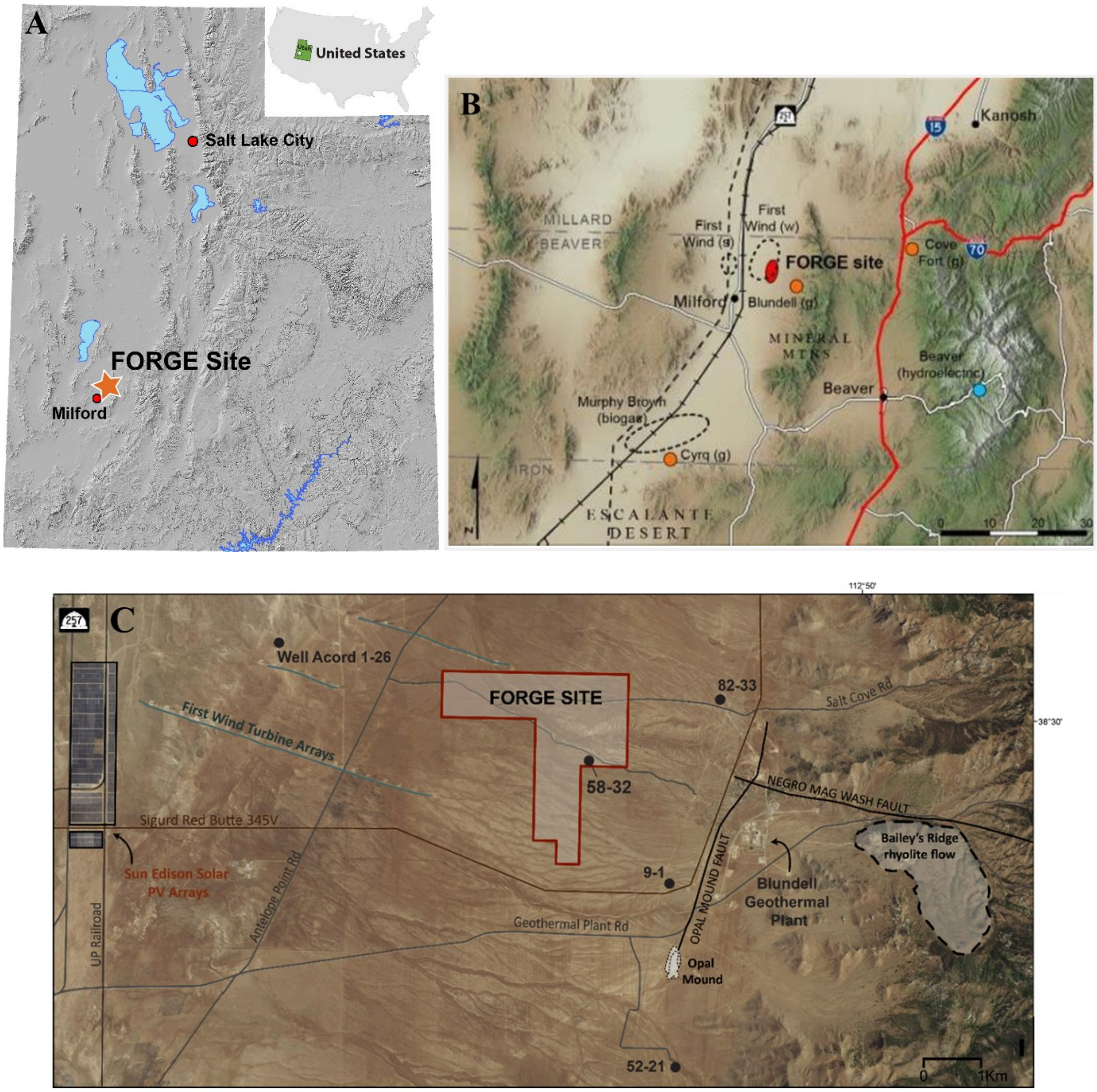

Figure 1: A) Location of the FORGE site. B) Distribution of renewable energy projects within Utah's Renewable Energy Corridor. The town of Milford is centrally located within the corridor, 16 km south of the FORGE site. C) Location of the FORGE site, key wells and energy projects. The Blundell power plant and production wells are located east of the Opal Mound fault.

3. GEOLOGY

The FORGE site is located on the eastern edge of the Milford basin, west of the Mineral Mountains. The geology of the central Mineral Mountains is dominated by a composite Tertiary pluton composed of diorite, granodiorite, quartz monzonite, syenite, and granite (Nielson et al., 1986) (Figure 2). U-Pb zircon dating indicates development of the plutonic complex began at 25.4 Ma (Aleinikoff et al., 1987), with emplacement of the hornblende diorite and continued until 8 Ma (Nielson et al., 1986; Coleman et al., 1997)

The Tertiary plutonic rocks intrude Paleozoic and Mesozoic sedimentary sequences exposed at the northern and southern ends of the Mineral Mountains and a thin belt of Precambrian gneiss on the west flank of the range. The Precambrian rocks have yielded a metamorphic age of ~1720 Ma (Aleinikoff et al., 1987). Quaternary (<1 Ma) rhyolite lava flows originating from domes along the crest of the range partially cover the granitic rocks. Temperatures of 250°C in the Roosevelt Hot Springs geothermal reservoir (Allis and Larsen, 2012) suggest the presence of a still cooling magma chamber in the shallow crust. None of the sedimentary or volcanic rock sequences were encountered in in any of the wells shown in Figure 2.

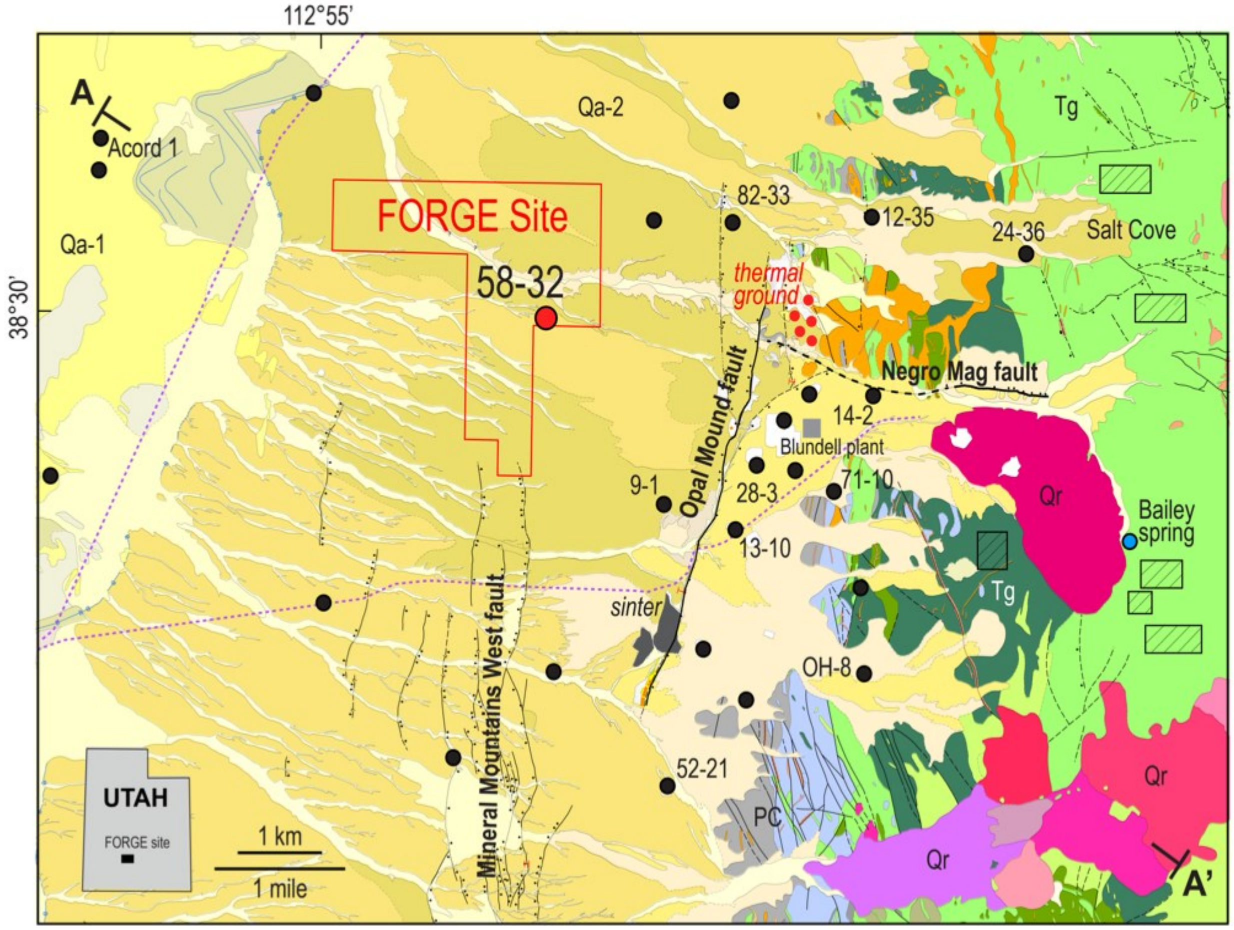

Figure 2: Geologic map of the FORGE site and surrounding area (modified from Nielson et al. 1986 and Kirby et al., 2018a). For clarity, only a few of the many wells are shown. See Figure 3 for cross section A-A'. Abbreviations: Qa-1=Lake Bonneville silts and sands; Qa-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoid; PC=Precambrian gneiss; Black filled circles=wells. Arrows show the direction of σ_{Hmax}. Stress data from 52-21 and 14-2 compiled by Davatzes (2016, written comm.)

Figure 3 illustrates the geology along an east-west cross section through the FORGE site. Unlike the steeply dipping range front faults characteristic of the Basin and Range Province, the contact between the granite and valley fill deposits dips at an approximately 30° to the west (Hardwick et al., 2016; Miller et al., 2018) The contact can be imaged across the FORGE site without evidence of major disruptions. It is marked by an intensely sheared rhyolite, interpreted to be a dike, in well 58-32 and by sheared granite in Acord 1. The seismic reflection image shown in Figure 3 illustrates the geometry of the contact where it passes through well 58-32.

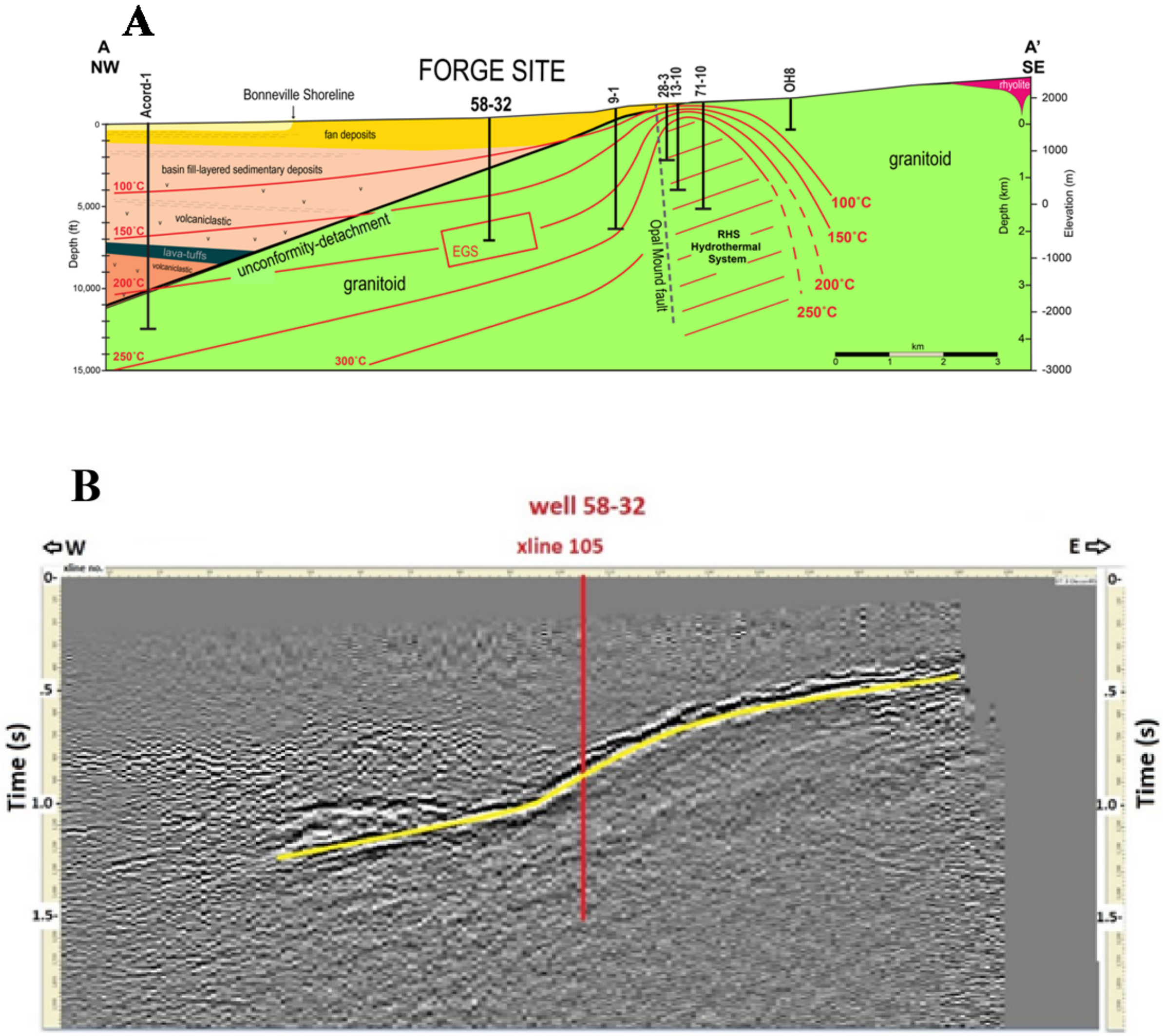

Figure 3. Cross section through well 58-32. A) Geology and temperature distributions along the NW-SE cross section A-A' shown in Figure 2. For simplicity, the term granitoid is used to describe the plutonic rocks. The Roosevelt Hot Springs geothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements. The red box represents the approximate position of the FORGE EGS reservoir (Kirby et al., 2018b). B) East-west time slice through well 58-32 (Miller, unpublished data). The top of the-basement contact is highlighted with a yellow line.

Coleman et al., (1997) interpreted the alluvial-basement contact as a rotated and eroded Basin and Range fault. based on: a) the presence of Precambrian rocks on the west flank of the Mineral Mountains; b) eastward dips of stratified rocks exposed in the range; c) Late Miocene dikes that dip 40-50° west but probably were originally vertical; and d) paleomagnetic data that, although too scattered to reliably quantify the magnitude, indicate eastward tilt of the plutonic complex. The lack of evidence for a large-offset west-dipping normal fault on the east side of the Mineral Mountains favors the isostatic rolling-hinge mechanism for tilting (Coleman et al., 1997), which implies that the range tilted as it was unroofed by faulting. These observations and the seismic imaging of the granite-alluvium contact suggest the top of the granite represents the partially eroded footwall of the west dipping normal fault that formed the Milford Basin.

The most prominent of the younger Basin and Range structures is the Opal Mound fault (Figure 2), 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). Temperature and pressure data demonstrate that the Opal Mound fault forms a hydraulic barrier separating the convective thermal regime at the Roosevelt Hot Springs geothermal system from the low permeability conductive thermal regime to the west, beneath the FORGE site (Figure 4).

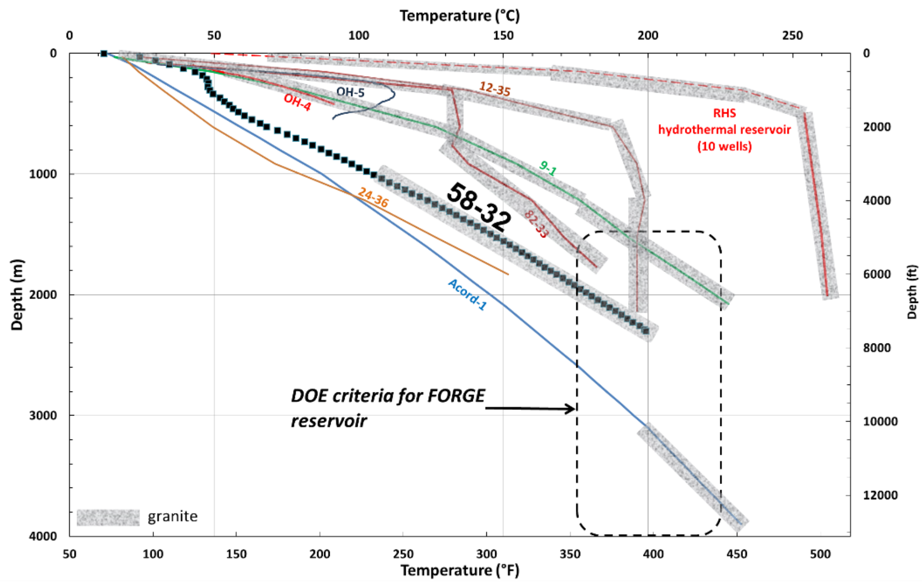

Figure 4. Temperature profiles in wells surrounding the FORGE site. The dashed rectangle shows conditions established by the U.S. DOE for a FORGE reservoir. See Figure 2 for well locations. Wells east of the Opal Mound fault within the Roosevelt Hot Springs geothermal system display convective thermal gradients. Wells displaying conductive gradients, including Acord-1, 82-33 and 9-1, 5 and 58-32 lie west of the fault (modified from Allis et al., 2016)

South of the Opal Mound fault, north-south trending faults form a series of short, narrow grabens and horsts (Nielson et al., 1986; Kleber et al., 2017). These faults die out to the north as the FORGE site is approached. New 3-D seismic reflection surveys and geochemical data indicate that these faults are shallow features that do not offset the contact between the basement and overlying basin fill deposits (Simmons et al., 2019).

The Negro Mag fault is another major steeply dipping fault, but it trends east-west (Figure 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 migrated southward and/or Proterozoic structures in the deep-seated basement (e.g. Dickinson, 2006; Wannamaker et al., 2015).

4. MICROSEISMICITY

Seismicity in the region surrounding the FORGE site has been monitored since 1981 (Figure 5). No events have been detected beneath the FORGE site. Analysis of the seismic catalogue for the time period 1 January 2000 to 30 June 2003 found an Mcomp = 1.5 for the site (Pankow et al., 2004). In late 2016, broadband seismometers were installed at sites FORU, FOR2, FOR3, and FOR4 (refer to figure 5 for locations) to improve detection of the seismic events. We currently estimate Mcomp to be close to zero. Since installation of the broadband array, 111 microearthquakes (M = -0.79 to 1.67) have been located under the Mineral Mountains to the east and southeast of the FORGE site. There is additional scattered seismicity to the south and west of the FORGE site.

Many of the events near the Opal Mound fault are relatively shallow and are located in the vicinity of the Blundell power plant bore field. This spatial association with the bore field suggests seismicity is related to injection and/or production. However, the magnitudes display no relationship to the volume of the injected fluid (Potter et al., 2017). Events to the east are deeper and appear to lie along a northwest trending fault zone defined by Zandt et al. (1982).

Analysis of the seismic data and faults surrounding the FORGE site suggests the risk of induced seismicity and seismic hazards is low (Pankow et al., 2017).

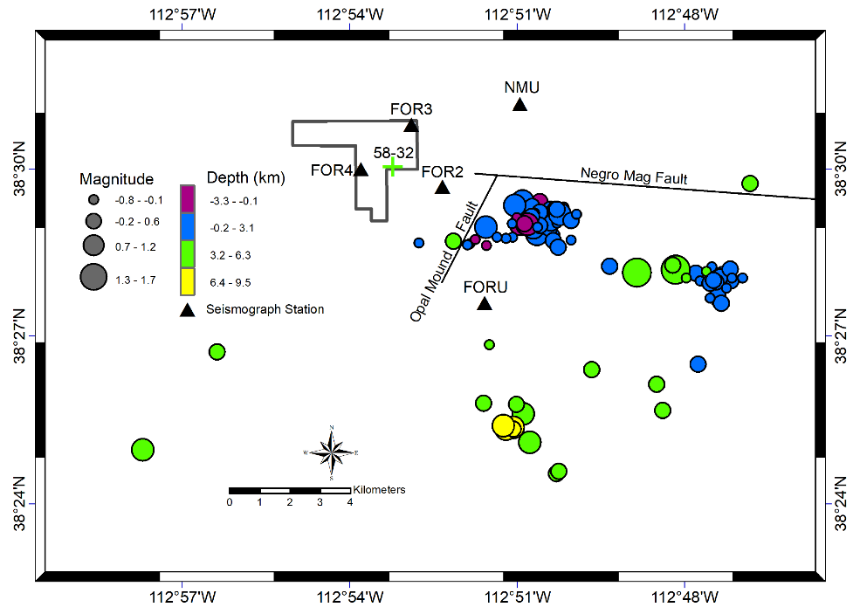

Figure 5. Locations and magnitudes of seismic events occurring near the FORGE site since 2016. Colored circles show the depth, size, and magnitude of the events. The green cross marks the location of well 58-32. No events have been recorded beneath the FORGE footprint since monitoring began in 1981. Magnitudes of seismic events range from -0.79 to 1.67.

5. WELL 58-32

Well 58-32 was drilled to a total depth of 2297 m (7536 ft). The well penetrated 1323 m (4340 ft) of low permeability, plutonic rocks consisting mainly of granite and quartz monzonite beneath 968 m (3176 ft) of undeformed alluvial deposits (Figure 6). Approximately 46 m (150 ft) of the well was left uncased for testing.

A full suite of geophysical and image logs was run in the hole from the 9 5/8-inch casing shoe at 662 m (2172 ft) to the base of the well. The Formation MicroImager (FMI) and SlimXtreme Sonic logs were rerun in the open hole section of the well after it was stimulated. Approximately 6.7 m (22 ft) of core was recovered from two intervals in the lower part of the well.

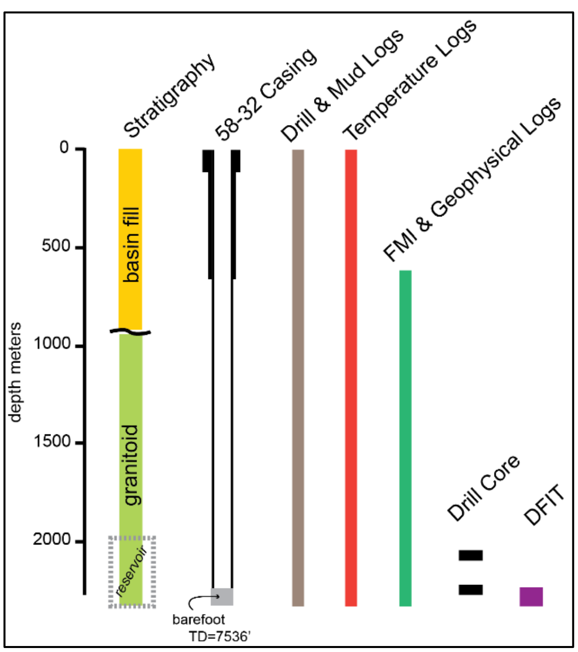

Figure 6. Summary of major activities conducted in well 58-32.

6. STRESS CHARACTERISTICS

More than 2000 natural fractures and 356 induced fractures were imaged, primarily in the plutonic rocks. In contrast, few fractures were observed in the overlying alluvial deposits between 662 m (2172 ft) and the base of the alluvial deposits at 968 m (3176 ft).

Some of these fractures were identified as induced, tensile fractures. Azimuths of the induced fractures indicate that the orientation of σ_{Hmax} trends NNE-SSW (Figure 7). A similar orientation was obtained from televiewer logs run in wells 14-2 and 52-21 (Keys, 1979; Davatzes, 2016, written comm.) (refer to Figure 2), indicating that stress directions are consistent across the region.

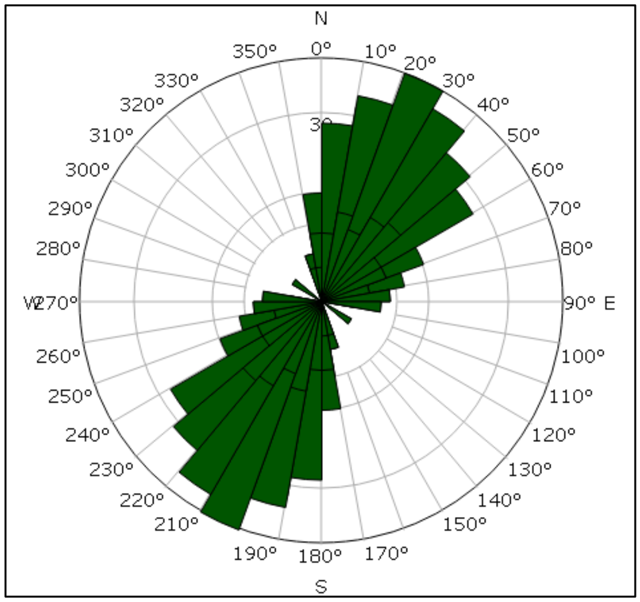

Figure 7. Azimuths of induced fractures in well 58-32. The orientation of the fractures indicates σ_{Hmax} trends NNE-SSW.

After the well was drilled, logged and cased, a packer was set near the toe of the production casing and the barefoot section was treated with multiple low rate injection cycles, two Diagnostic Fracture Injection Test (DFIT) type measurements, and a step rate test. Due to the low permeability of the rocks, poroelastic effects are likely minimal but thermoelastic stress modification is possible.

The injection data were analyzed using accepted stress determination protocols. These included diagnostic and square root of time evaluations, and two different interpretations of the G-function (see for example, Economides and Nolte, 2000; McClure et al., 2014). Gradients based on G-function analyses (measurements using the tangent and the compliance techniques for closure stress assessment) ranged from 14.0 kPa/m (0.62 psi/ft) for σ_{Hmin} to 17.4 kPa/m (0.77 psi/ft) for σ_{Hmax}. A gradient of 25.6 kPa/m (1.13psi/ft) was determined for the vertical stress. σ_V was estimated by integration of the density log from depth to the surface. These stress relationships are indicative of a normal faulting regime.

Some of the highlights of this injection program are:

- Permeability within the reservoir rocks is controlled by fractures. Transmissibility was determined from the first DFIT measurement to be 4.5 md-ft, suggesting a permeability of about 30 microdarcies.
- No breakdown pressure was evident as a result of low-rate injections designed to assess the possibility of significant shear fracturing (hydraulic shearing) at pressures below the minimum principal stress. However, there is some evidence that shearing may have occurred in conjunction with hydraulic fracturing. Stimulations planned for will further address the possibility that shearing occurred.
- Very rich post-shut-in and after closure data were generated. All of the data are publicly available. Of particular interest are significant multiple peaks on the semilog derivative curves that can be attributed to significant access to pre-existing fractures (Figure 8).
- Inflections in the real-time bottom hole temperature during shut-in may be indicators of fracture closure in the near-wellbore environment (Figure 9).
- Aperture enhancement of the induced fractures is apparent from a comparison of the FMI logs run before and after injection (Figure 10). Some of this change could be thermoelastic. During the last injection stage, 200 mesh calcium carbonate was pumped to partially prop fractures taking fluid.

7. WHAT WILL HAPPEN IN 2019?

In the spring of 2019, the open hole section of well 58-32 will be treated before perforating and testing two shallower zones. Using the legacy FMI, the first perforated zone will be aligned with natural fractures that are believed to be near-critically stressed, to explore the possibility of shearing and self-propping. The second perforated completion will cover natural fractures with orientations believed to be unfavorable to shearing. In each zone, after the low rate hydraulic shearing evaluations, DFITs will be run. Flowback (Savitski and Dudley, 2011) and “micro-impulse” testing is also planned to develop technologies to minimize shut-in time in this low permeability environment.

Microseismicity will be monitored during the stimulations. Two monitor wells will be drilled, one approximately 915 m (3000 ft) deep and second shallower well to 304 m (1000 ft). A Distributed Acoustic Sensing (DAS) cable cemented in the annulus of the production casing and a string of geophones will be installed in the casing of the deep monitoring well. Two geophones will be installed in the shallow well. In addition to the existing surface broadband seismometers, a nodal array of 150 seismic sensors will be deployed.

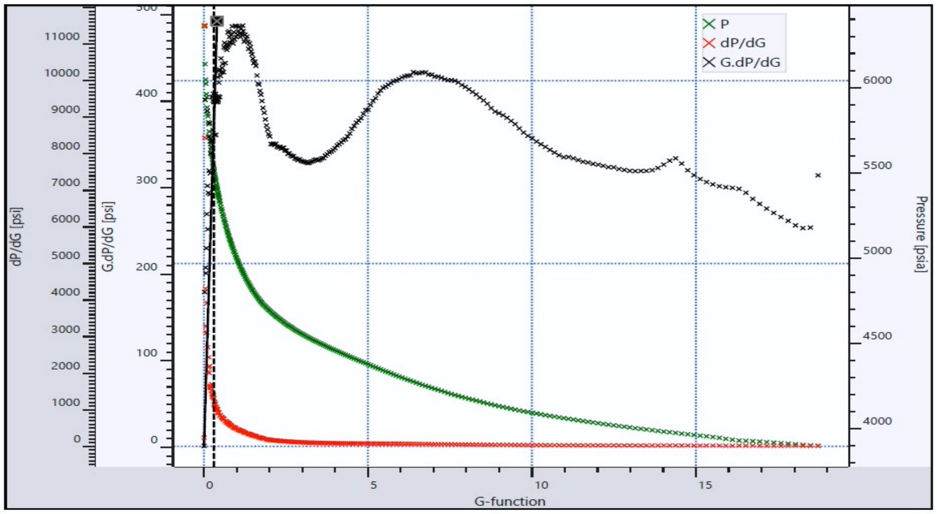

Figure 8. The rich character of the post-shut-in data is intriguing. Two major humps are present indicating the closure of two fracture sets inferred to be natural and induced fractures (the third hump is probably an operational artifact).

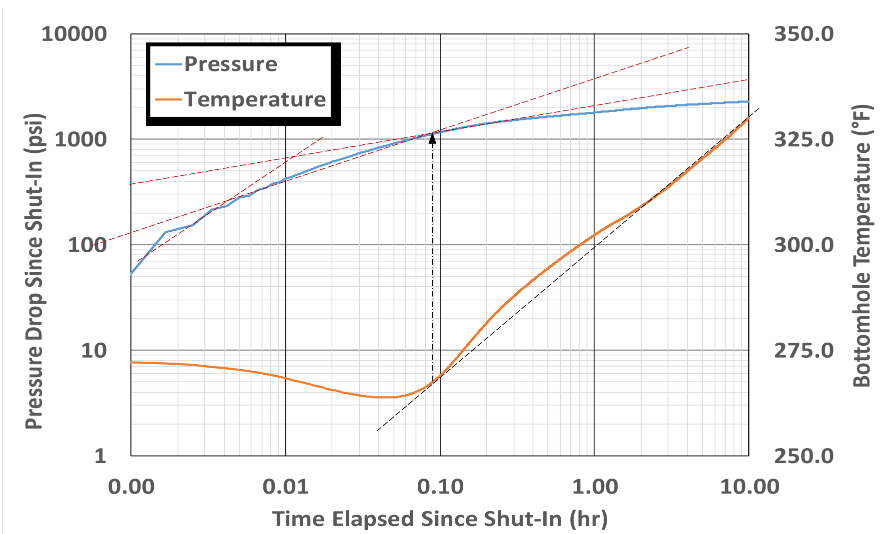

Figure 9. Shown on a simple diagnostic plot, the temperature rebound coincided with the end of a half slope. This relationship suggests temperature may be diagnostic of indicators of fracture closure in the near-wellbore environment.

In the fall of 2019, we will initiate full development of the FORGE laboratory with the drilling of a near horizontal injection well from a pad west of well 58-32. The well will be drilled to the southeast, cased, cemented and hydraulically fractured in three short stages at the toe (Figure 11). Microseismicity will be monitored. The production well will be drilled in 2020 above the injector and geosteered to intersect the microseismic cloud generated during the hydraulic stimulation. The bulk of both of wellbores will be intact at this point. The FORGE team will issue Funding Opportunity Announcements (FOAs) in 2019 and each year thereafter for development and testing under the topics of reservoir characterization, creation and sustainability. Research areas of critical importance to EGS development include high temperature drilling tools, novel stimulation and well completion technologies, monitoring and management of the fracture network, forecasting of induced seismicity, stress management, and numerical simulations.

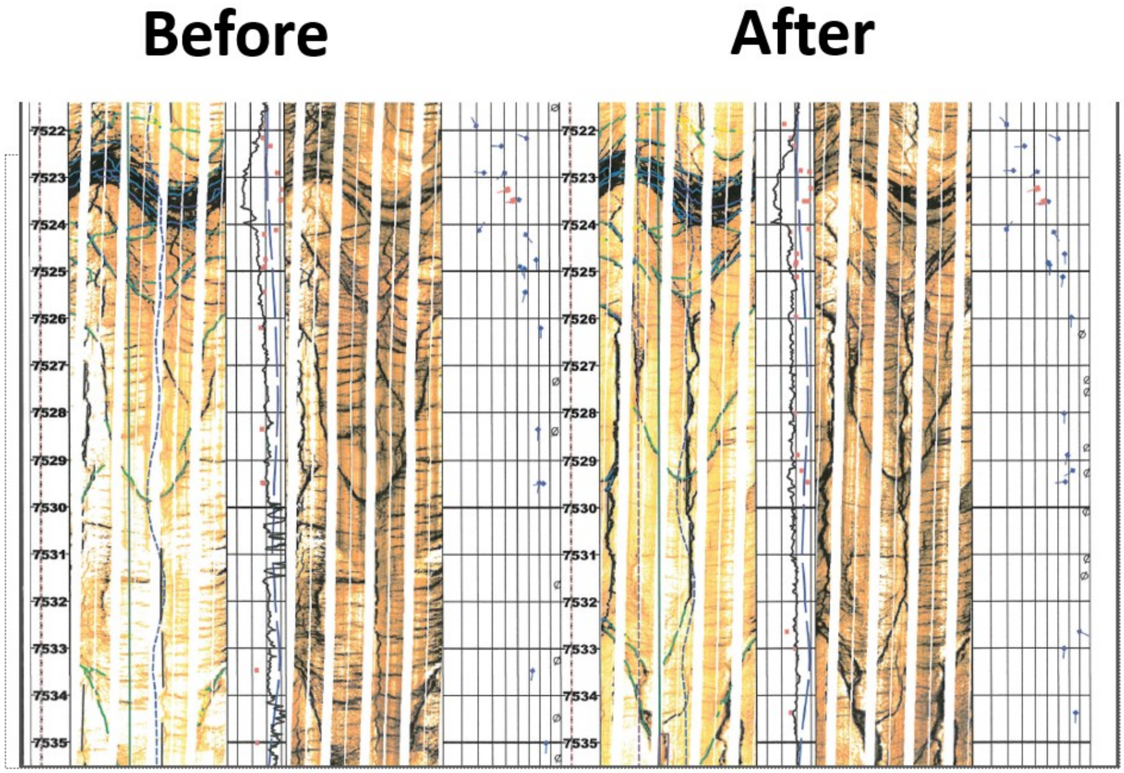

Figure 10. Formation MicroImager (FMI) scans run before and after stimulation of the barefoot section of well 58-32. The induced fractures (vertical fractures) visible in the log run after the stimulation show a clear increase in width and continuity compared to the pre-stimulation log. Temperatures were similar before and after the stimulation, suggesting cooling was not the cause of fracture enhancement. Drilling- or thermally-induced axial fractures presumably indicate the maximum horizontal principal stress direction, which in this case trends NNE-SSW, consistent with geologic indicators in the surrounding region.

This is a challenging working environment, with high temperatures that could exceed 200°C and hard, abrasive rock. To put the rock in perspective, drilling rate in the granite for well 58-32 was on the order of ~3-4 m/hr (~10-13 ft/hour). Improvements in drilling technology are essential, along with being able to create a regular network of hydraulic fractures that will allow effective heat transfer to the working fluid.

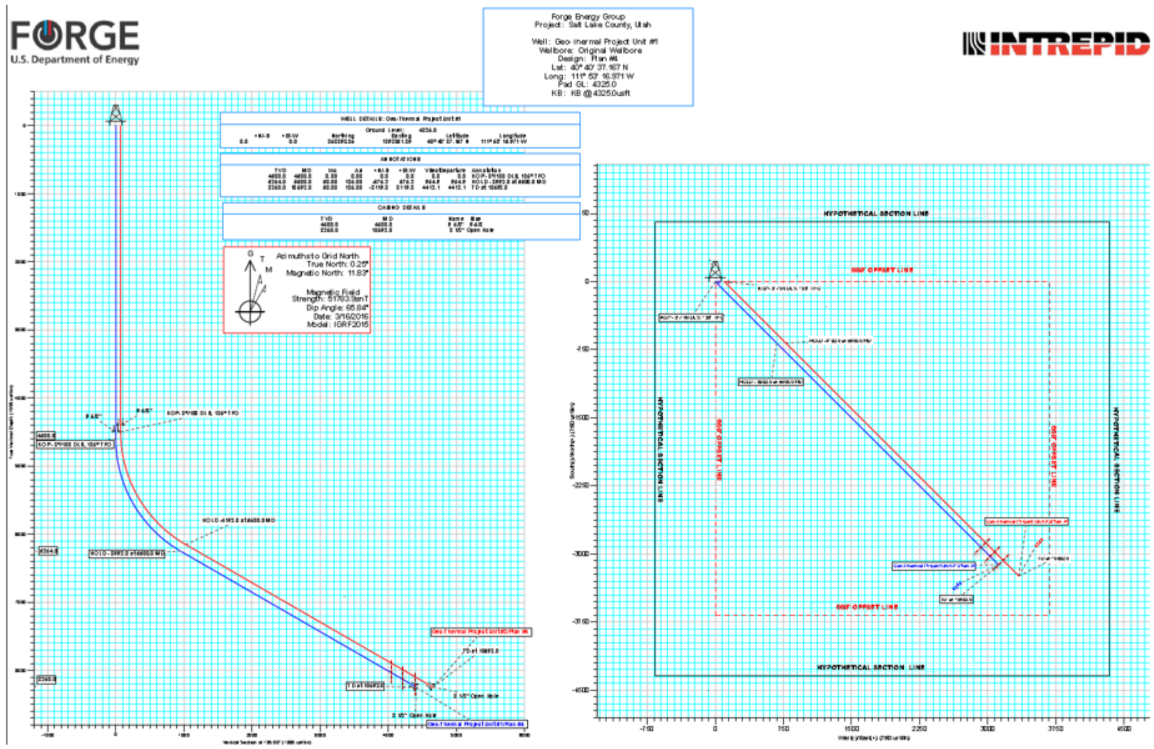

Figure 11. Conceptual elevation view (left) and plan view (right) of an injection well with a production well overlying it and interconnecting hydraulic fractures at the toe. The pristine part of the wellbores will be allocated to DOE-funded research. In a commercial situation, stages would be treated all along the lateral length. These laterals are shown at 60°to the vertical, although drilling at a higher angle may be possible.

All data are available upon request and on line through the NGDS (National Geothermal Data System).

CONCLUSION

The Milford FORGE site is located in south-central Utah adjacent to the Mineral Mountains. Data from nearly 100 deep and shallow wells, integrated with the results of new geologic mapping, results from well 58-32 drilled to a depth of 2296 m (7536 ft) on the FORGE site, and 3-D seismic reflection, gravity, and geochemical surveys has provided a detailed picture of the geological, thermal and stress characteristics of the FORGE reservoir.

Well 58-32 reached a temperature of 199°C (390°F) after penetrating 1323 m (4340 ft) of low permeability plutonic rocks consisting primarily of granite, quartz monzonite and monzonite. The contact between the overlying undeformed alluvial deposits and the plutonic rocks is interpreted to represent a rotated Basin and Range fault dipping 20-30° to the west.

Induced fractures identified in the Formation MicroImager (FMI) log of the well trend NNE-SSW, the direction of σ_{Hmax}. Stress gradients determined from injection tests in the open hole section of the well ranged from 14.0 kPa/m (0.62 psi/ft) for σ_{Hmin} to 17.4 kPa/m (0.77 psi/ft) for σ_{Hmax}. A gradient of 25.6 kPa/m (1.13 psi/ft) was calculated for σ_V. Comparison of pre and post injection FMI logs document enhancement and growth of the induced fractures, providing evidence the stress field is appropriate for EGS development.

Three stimulations are planned for well 52-32 in 2019; one in the open hole section of the well below 2248 m (7375 ft) and two in the cased portion of the well below 1981 m (6500 ft), where temperatures exceed 175°C. The stimulations will evaluate the behavior of fractures with different orientations at injection rates higher than those achieved during the 2017 stimulations. These stimulations will provide a critical test of the seismic monitoring system. Drilling of the injection and production well pair, and creation of an EGS reservoir,

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