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Current Activities at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE)

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ABSTRACT

The U.S. Department of Energy's (U.S. DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) is a field laboratory where tools and technologies required for creating, sustaining, and managing Enhanced Geothermal Systems (EGS) can be tested under reservoir conditions. This paper provides an update of activities occurring at the Utah FORGE site in south-central Utah.

Since 2016, six wells have been drilled, the deepest reaching a depth of 9,500 ft (2895.6 m) and an estimated temperature of 465°F (241°C). The vertical wells will be used for microseismic monitoring and tool testing. The sixth well, 16A(78)-32, was deviated 65° from vertical, before reaching a total depth of 10,987 ft (3,348.8 m) MD and a true vertical depth of 8,561 ft (2,609.4 m). Injection tests indicate a minimum horizontal stress gradient of 0.74 psi/ft (16.74 kPa/m) and very low permeability of ~20 micro-Darcies.

The wells encountered similar lithologies. With depth, the wells penetrated alluvium above the crystalline basement rocks that will form the geothermal reservoir. The contact dips west at 20-35° and is interpreted to be a rotated and eroded Basin and Range bounding fault. The basement rocks consist mainly of Tertiary plutonic rocks ranging in composition from granite to monzodiorite. Sheared rhyolite emplaced along the alluvial-basement contact is interpreted to be a Tertiary dike. In the deepest parts of well 16A(78)-32, interfingering Tertiary granite and sillimanite-bearing Precambrian metamorphic rocks were encountered.

A three-stage stimulation was conducted near the toe of well 16A(78)-32 in April 2022. Two of the stages were performed in the cased portion of the well. Slickwater was pumped in the lower zone and a viscosified fluid in the upper zone, both at 35 bpm (5.56 m^3/min). Slickwater was pumped at 50 bpm (7.95 m^3/min) in the open hole section of the well. Drilling of the production well and reservoir creation is planned for 2023.

Seismicity has been monitored since 1981 - no tectonic events have been detected below the Utah FORGE site. Seismicity is monitored continuously. The permanent monitoring system consists of concentric rings of near-surface borehole seismometers, surface accelerometers, a seismometer/accelerometer deployed at shallow depth, and Distributed Acoustic Sensing (DAS) cables cemented at mid-depths. During the April 2022 stimulation, the permanent monitoring system was enhanced with geophone strings at reservoir depths in the three deepest vertical wells, an integrated DAS/3-component geophone system, and a surface DAS cable and nodal array.

All Utah FORGE data, including data collected by externally funded R&D projects can be accessed through the Geothermal Data Repository.

In this paper, we provide an update on activities at the Utah FORGE site.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) offer the greatest potential for meeting the U.S. Department of Energy's (DOE) goals of 60,000 MWe by 2050 and reducing the cost of electricity by 90% to $45 per MW-hour. Since the late 1970s, more than a dozen EGS projects have been conducted throughout the world in an effort to create geothermal reservoirs where none exist naturally. None of the projects have achieved commercial scale levels of production.

In 2014, the DOE established the Frontier Observatory for Research in Geothermal Energy to de-risk and test techniques for creating, sustaining and monitoring EGS reservoirs. The ultimate goal of the Utah FORGE field-scale 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 (Moore et al., 2020, 2021).

The Utah FORGE site is located 200 miles (~322 km) south of Salt Lake City in Utah's Renewable Energy Corridor (Figure 1). Nearby operating renewable projects include a 306 MWe wind farm, a 240 MWe solar field, the 36 MWe Blundell geothermal plant at Roosevelt Hot Springs, and a biogas facility that produces renewable natural gas from local hog farm operations.

The region surrounding Utah FORGE is uninhabited because the local groundwater chemistry precludes its use for human consumption or agricultural purposes. Water rights to the groundwater have been obtained from the State of Utah for site operations. Milford, located 10 miles (16 km) south of the site is the closest community. It has a population of 1700 and can provide most of the project's daily needs, including lodging, food and sundry supplies and water for drilling and injection testing.

Scientific investigations around the Utah FORGE site have been ongoing since the late 1970s. More than 80 shallow (<500 m) and 20 deep (>500 m) wells were drilled and logged in support of geothermal development at Roosevelt Hot Springs. Since the Utah FORGE project began, the early scientific data have been augmented with detailed seismic reflection, LiDAR, InSAR, gravity, magnetic, groundwater and magnetotelluric surveys, geophysical, temperature and image logs of all Utah FORGE wells, and detailed geological mapping. An overview of the geoscientific attributes of the project are reported in Allis and Moore (2019 and references therein) and in subsequent topical reports available through the Geothermal Data Repository (GDR). These data have yielded a very complete picture of the regional geologic setting (Figure 2).

2. GEOLOGIC SETTING

Utah FORGE is located on young alluvial fan deposits that dominate the near surface stratigraphy (>2000 ft (609.6 m) thick) of North Milford valley (Figure 2). Beneath the Utah FORGE site, the alluvial deposits consist of sand-sized fragments to boulders of crystalline rocks in a fine-grained matrix of quartz, feldspar and minor mafic minerals derived from Mineral Mountains. West of the site, in well Acord-1-26 12,646 ft (3854.5 m), the basin sequence consists of horizontally bedded mafic lava flows, ash-flow tuffs and younger fine-grained sedimentary deposits lying unconformably on the crystalline basement. The contact with the basement is interpreted as an eroded, near vertical Basin and Range fault of Miocene age, that was rotated down to the east, forming a gently undulating ramp dipping 20-35° west (Coleman et al., 2001; Bartley, 2019). This and related subparallel structures in the basement are believed to have accommodated large-scale down-dip displacement of >10 km between 10 and 6 Ma, but as a consequence of block rotation are now inactive (Bartley, 2019).

Within the Utah FORGE wells and the adjacent Mineral Mountains, the basement consists mainly of granite and quartz monzonite, with lesser granodiorite, quartz monzodiorite, and diorite (Jones et al., 2019, 2021) ranging in age from 26 to 8 Ma (Aleinikoff et al., 1987; Coleman and Walker, 1992; Coleman et al., 2001). In this paper the granitic rocks are collectively referred to as granitoid. Sheared rhyolite occurring along the contact between the basin fill and basement rocks is interpreted as a dike emplaced within the Basin and Range fault zone.

Paleozoic limestone, dolomite, quartzite and phyllite are widely exposed in the northern and southern parts of the Mineral Mountains but only a few scattered outcrops of limestone and quartzite occur east of the Utah FORGE site. Locally, tungsten mineralization is present along the contact with the granitoid. At depth, narrow rafts of metamorphosed limestone and quartzite are found in the deepest part of well 56-32.

Precambrian rocks are exposed on the western edge of the Mineral Mountains (Nielson et al., 1986; Kirby, 2019) and were encountered in the deepest portions of wells 16A(78)-32, 58-32 and 78B-32 where they are encapsulated in the granitoid. These 1.7 Ga rocks are distinguished by the presence of sillimanite, and locally are strongly folded (Aleinikoff et al., 1987) (Figure 3). Much of the reservoir will be developed in these interfingering granitoid and metamorphic rocks.

Magmatic activity that began in the Tertiary has continued, at least sporadically through the Quaternary. The most recent evidence of magmatism resulted in the eruption of young rhyolite centers (0.5-0.8 Ma) in the Mineral Mountains (Lipman et al., 1978). Elevated He^3/He^4 values are consistent with magmatic degassing west of the Utah FORGE site (S. Simmons, pers. comm. 2022).

In addition to the main north-trending Basin and Range structure that separates the basin deposits from the basement rocks, three major structures have been identified (Kirby, 2019; Knudsen et al., 2019; Simmons et al., 2020). The Opal Mound and Mag Lee faults appear to be near vertical, small offset structures. The north-trending Opal Mound fault separates the convective thermal regime to the east in the Roosevelt Hot Springs geothermal system from the conductive regime, characteristic of the Utah FORGE site to the west. The east-west trending Mag Lee fault appears to mark the northern edge of the convective regime. The Mineral Mountains West fault system represents a corridor of north-south trending fault scarps (<5 m high) in fan deposits extending southward from the Utah FORGE site. Interpretation of reflection seismic surveys (Miller et al., 2019) suggest these faults sole-out along the main Basin and Range fault at the basement contact.

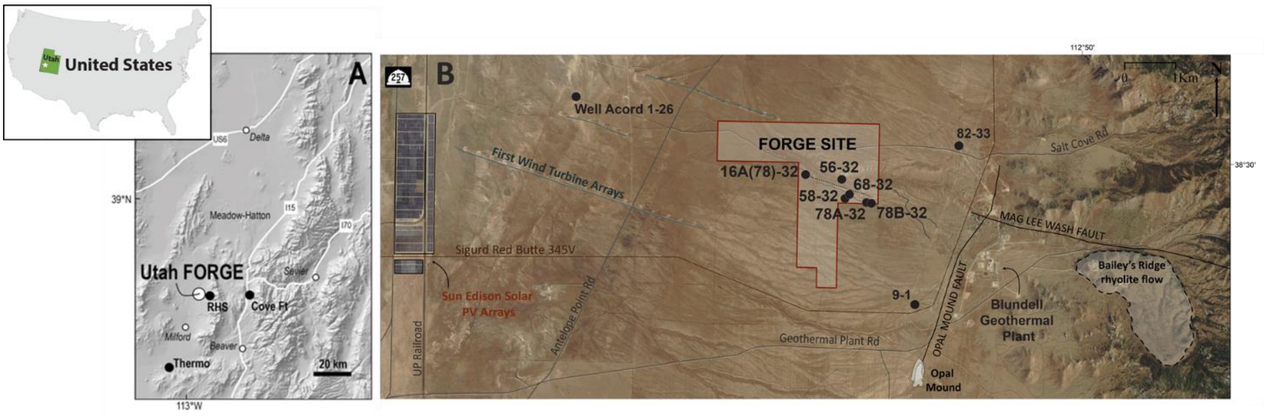

Figure 1: Location maps of the Utah FORGE site. A) Map of southwest Utah. Geothermal fields: RHS=Roosevelt Hot Springs; Cove Ft= Cove Fort; Thermo . B) Expanded view of the area immediately surrounding the Utah FORGE site. Blundell geothermal power plant is located at RHS.

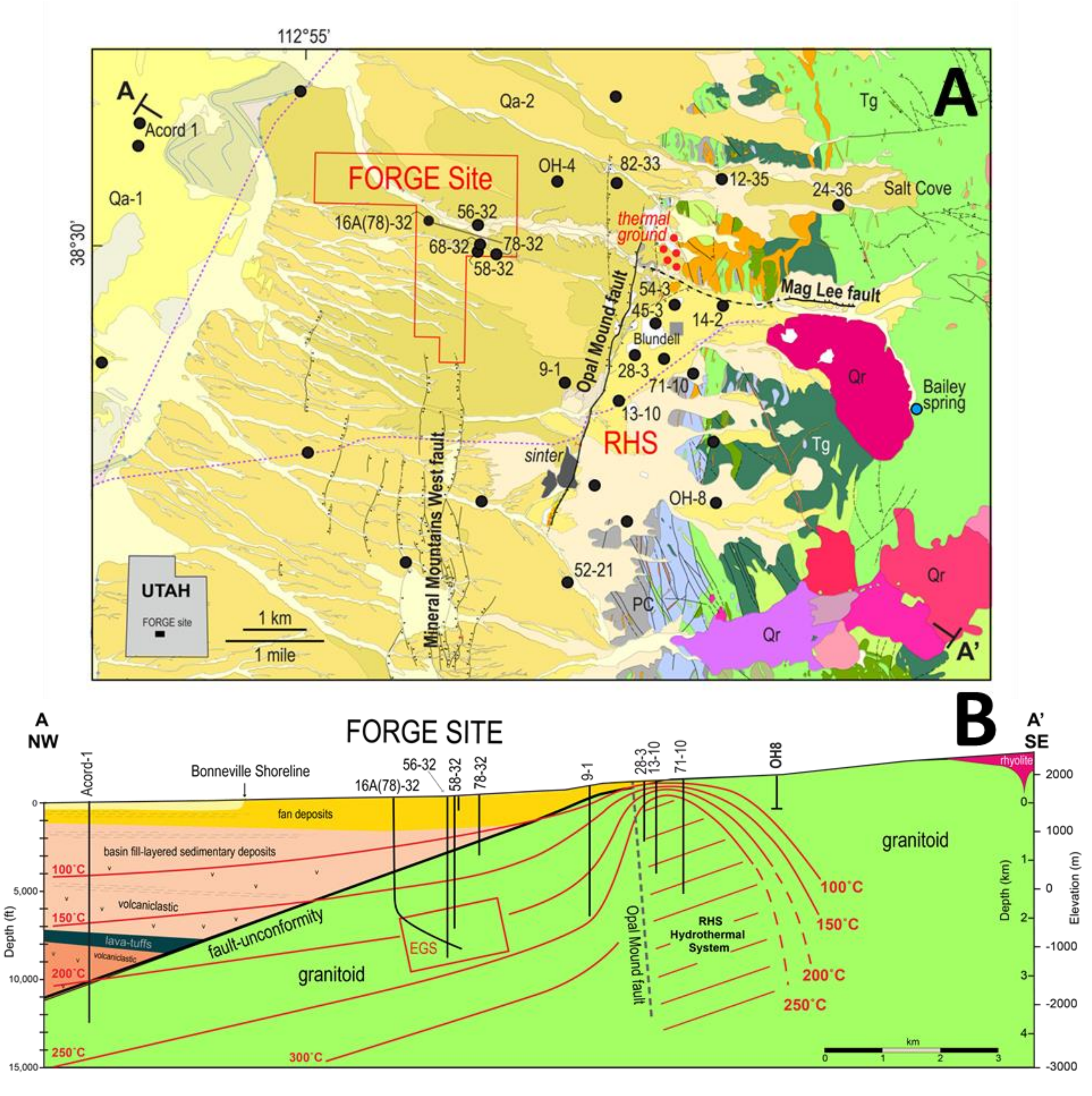

Figure 2: A) Geologic map of the Utah FORGE site and surrounding area (modified from Nielson et al. 1986 and Kirby, 2019), For clarity, only a few of the many wells are shown. Abbreviations: Qa-1=Lake Bonneville silts and sands; Qa-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoid; PC=Precambrian gneiss; black filled circles=wells. B) Northwest-southeast section showing the distribution of the

main rock types, the contact between the basement granitoid and the overlying basin fill stratigraphy, and the thermal structure. The Roosevelt Hot Springs (RHS) hydrothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements. The red box represents the approximate position of the EGS reservoir.

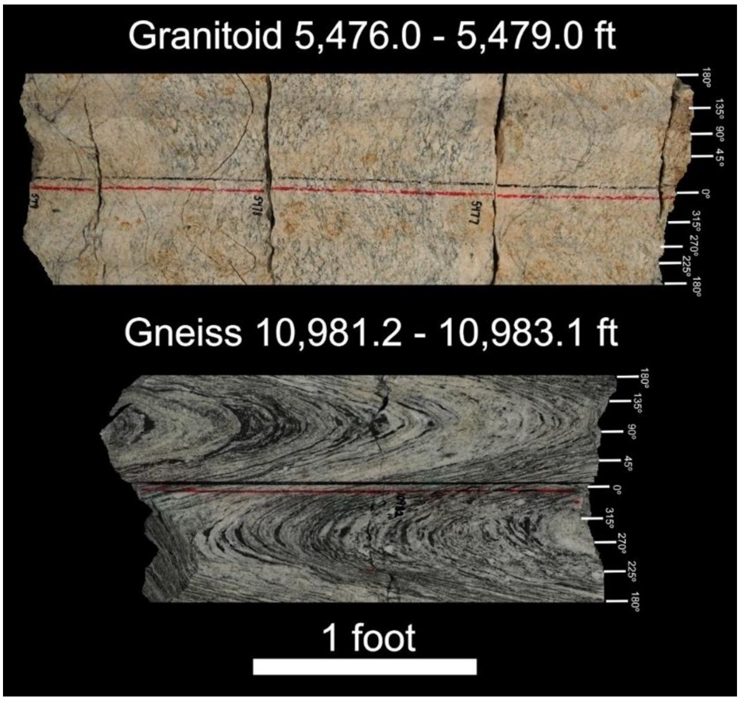

Figure 3: Stitched photos that give a 360º view of two core samples from well 16A(78)-32. The upper core interval is a sample of the granitoid, and the lower core interval is a sample of the tightly folded banded gneiss (Jones et al., 2019).

3. DRILLING RESULTS

Since the Utah FORGE program was initiated, six deep wells have been drilled. The locations of these wells and their depths are shown in Figure 4 and Table 1. Five of the wells, 56-32, 58-32, 68-32, 78-32, and 78B-32 are vertical. These wells are being used for seismic monitoring and tool testing. The sixth well, 16A(78)-32, will serve as the injection well during the creation of the reservoir. Well 16A(78)-32 was deviated at 65° to the vertical and drilled to a measured depth (MD) of 10,987 ft (3,348.8 m), approximately parallel to the minimum horizontal stress direction. The was completed with 7-inch (177.8 mm) casing to a depth of 10,797 ft (3,290.9 m), leaving the remainder of the hole open for testing. To our knowledge, this is the first time a large diameter highly deviated well has been drilled for geothermal purposes. Well 16B(78)-32, will serve as the production well of the injection-production pair. This well will be drilled parallel and approximately 328.08 ft (100 m) above well 16A(78)-32 in 2023. All of the wells have been extensively logged. The logs can be accessed through the Geothermal Data Repository (GDR) and the Utah FORGE website (www.utahforge.com).

Cuttings samples were collected every 10 ft (3.048 m) while drilling the wells. The samples examined under a binocular microscope, then analyzed in thin sectioned and by X-ray diffractometry to determine their primary and secondary mineralogy. In addition to the cuttings, a total of 151.2 ft (46.09 m) of core was retrieved from wells 16A(78)-32, 58-21 and 78B-32 (refer to Figure 3).

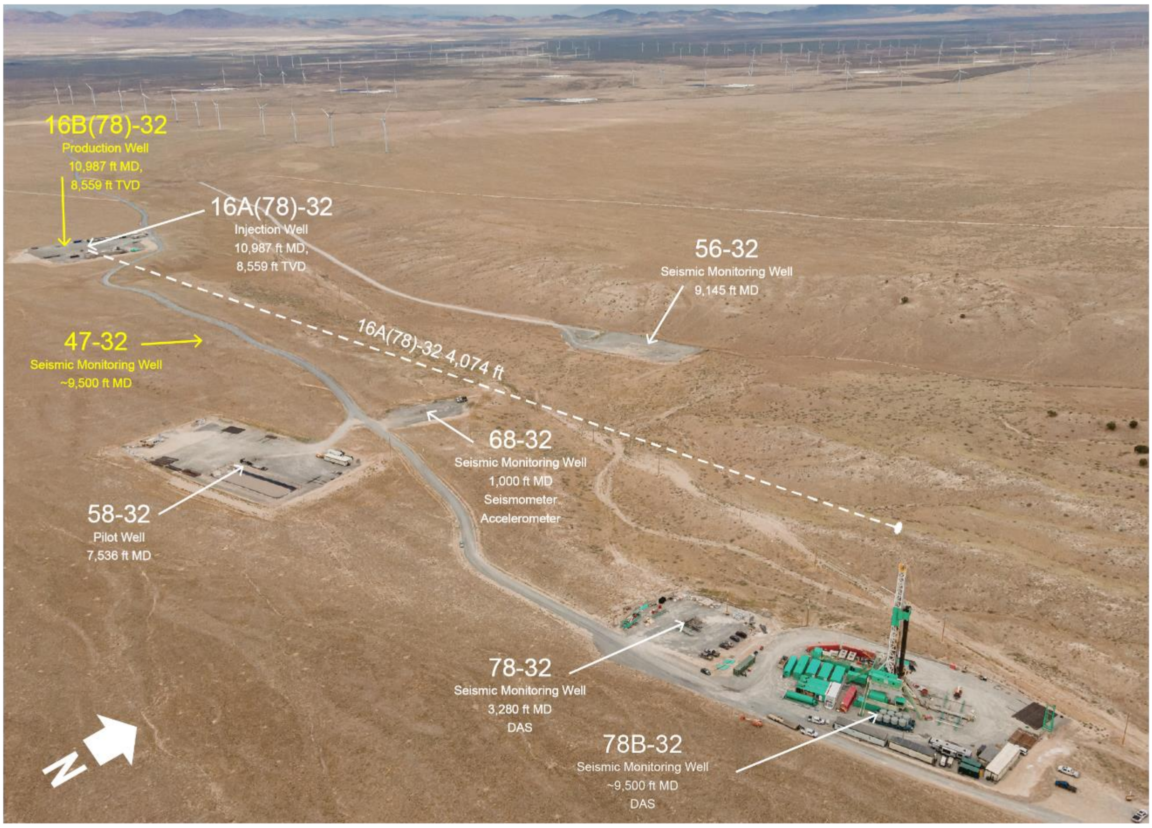

Figure 4: Aerial photo looking northwest across the Utah FORGE site showing the well locations and the trajectory of well 16A(78)-32 (white dashes).

Table 1: Utah FORGE well data.

Well	MD (ft)	TVD (ft)	Top of Basement (ft)	Bottom of Casing (ft)	Open Hole (ft)	Temperature (F/C)
58-32	7,536	7,527	3,176	7,389	147	386/199
78-32	3,280	n/a	2,560	3,268	12	224/107
68-32	1,000	n/a	n/a	980	20	n/a
16A(78)-32	10,987	8,559	4,150	10,787	200	429/221
56-32	9,145	9,138	3,025	9,105	40	435/224
78B-32	9,500	9,497	2,350	8,508	992	465/241 (est)

Despite challenging drilling conditions, progressive improvements in the rates of penetration (ROP) were achieved with each succeeding well (Figure 5) (Dupriest and Noynaert, 2022). An ROP of close to 100 ft (30.48 m) per hour was reached in the most recently drilled well, 78B-32, setting a new record for a single bit run in granitoid. The efficient drilling performance is attributed to the use of PDC bits manufactured by Reed-Hycalog and optimizing drilling parameters by continuous monitoring of Mechanical Specific Energy (MSE), which is the amount of energy required to remove a unit volume of rock (e.g., Rickard et al., 2019). Although excellent results were achieved, reducing hole rugosity while maintaining a high ROP remains an important goal.

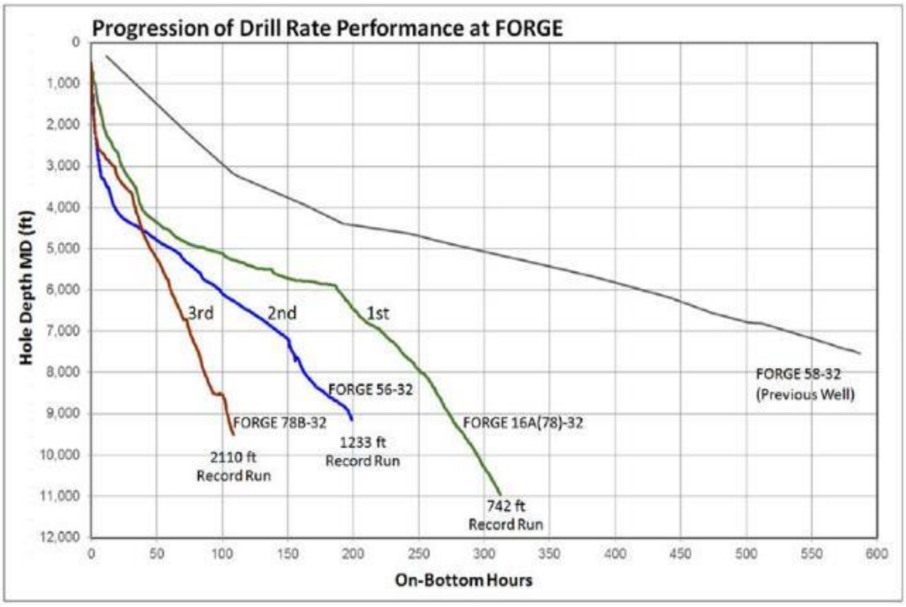

Figure 5: On-bottom rotating hours in sequentially drilled wells at Utah FORGE (Dupriest and Noynaert (2022).

4. STRESS CHARACTERISTICS

Understanding the stress directions and magnitudes is one of the essential lessons learned from past EGS projects. Formation Microscanner Image (FMI) logs document the presence of four sets of natural fractures in the basement rocks, with the majority trending north-south and dipping moderately to the west at ~60° (Figure 6). Well 58-32, was the only well logged through the basin deposits. Despite the presence of intense deformation of the underlying basement, few fractures are present in the alluvium, suggesting much of the deformation occurred prior to basin filling. Near vertical fractures trending NNE-SSW were also observed in the image logs throughout the basement. These fractures are interpreted as induced fractures formed parallel to the maximum horizontal stress direction. Their orientation is consistent with those determined from wells 14-2 and 52-21 in the Roosevelt Hot Springs Geothermal system (Keys, 1979) (refer to Figure 2 for well locations), indicating that stress directions are consistent across the region.

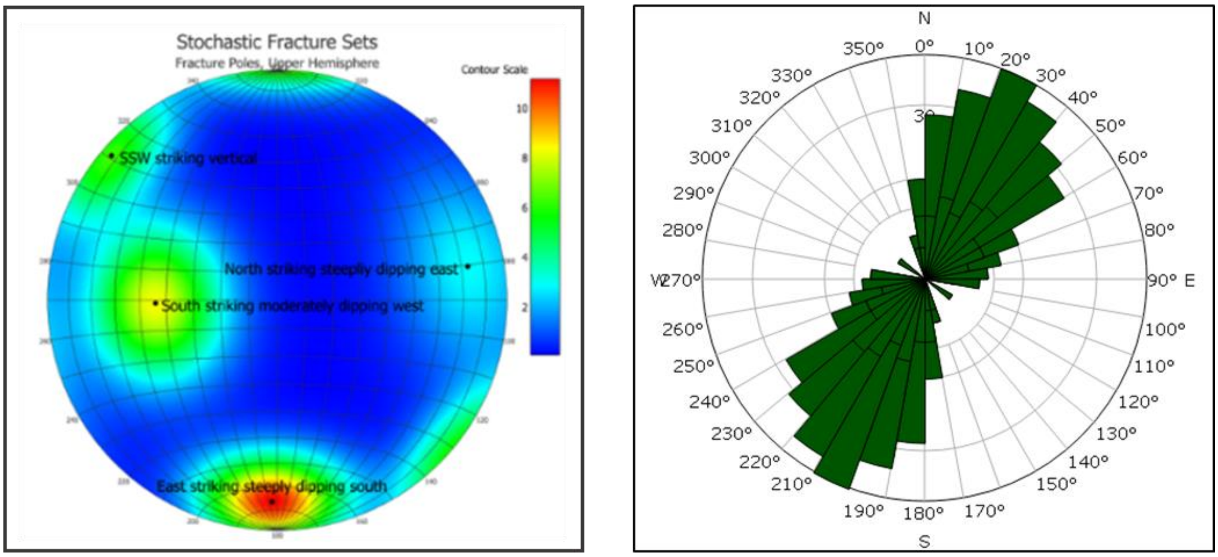

Figure 6: Fracture orientations in well 58-32. Left: Orientations of natural fractures. Right: Azimuths of induced fractures. The orientation of the fractures indicates the maximum horizontal stress direction trends NNE-SSW.

Several injection tests were conducted at the Utah FORGE site. In 2017 and again in 2019, low volume-low rate injection tests were conducted in well 58-32 (Xing et al., 2020; Xing, Damjanac, 2021). The earliest tests were performed in the 147 ft (44.81 m) of open hole at the toe of the well at rates up to 9 bpm (1.43 m^3/min). In 2019, fluid was again injected during a low volume Diagnostic Fracture Injection Test (DFIT) into the open hole section and in two zones behind casing at rates up 15 bpm (2.38 m^3/min) (Xing et. al., 2020). Based on these tests, the minimum horizontal stress is estimated to be 0.74 psi/ft [16.74 kPa/m] (Xing et al., 2020; Xing, Wray et al., 2022; McLennan et al., 2023). Laboratory measurements on core and the DFITs yielded very low permeabilities of 20-80 micro-Darcies (Energy & Geoscience Institute, 2018; Forbes et al., 2019; Xing, Winkler, Swearingen, 2021).

After completing well 16A(78)-32 in 2021, a DFIT was conducted in the 200 ft (60.96 m) of open hole at the toe of the well (Xing, Winkler, 2021). The pressure data indicate a hydraulic fracture was created at a pump rate of much less than 1 bpm [0.159 m^3/min] followed by a slow pressure decline after shut-in. The low decline rate suggests that leakoff to the formation (matrix and natural fractures) would not present a major design challenge for subsequent injection tests (McLennan et al, 2023).

In 2022, three high-rate high volume step rate stimulations were performed near the toe of well 16A(78)-32 (see McLennan et al., 2023 for details of the test program and results). The test design incorporated numerical models of Discrete Fracture Networks (DFNs) that integrated Formation Microimager (FMI) logs and surface mapping (Finnila et al., 2019, 2021; WSP Golder, 2022). Multiple scenarios were tested to predict hydraulic fracture propagation behavior at different pumping rates, fracturing fluid viscosities, and formation mechanical properties (Xing et al., 2021; Willis and Podgorney, 2023). The final injection program consisted of three fracturing stages; one stage in the 200 ft (60.96 m) of open hole at the toe of the well and two stages in the cased portion of the well at slightly shallower depths.

The first stage consisted of slickwater, pumped at rates up to 50 bpm (7.95 m^3/min) in the open hole section of the well. After 4,261 bbl (677.4 m^3) were pumped, the well was shut in for 4 hours before being flowed back. A surface formation breakdown pressure of 4,090 psi (28.2 MPa) was recorded early in the injection cycle at 5 bpm (0.795 m^3/min), but the low rate and pressure is likely to have been influenced by previous testing. After a shut-in period 4 hours, well was flowed back for 16.5 hours. A total of 2,331 bbl (371 m^3) (55%) the injected fluid was recovered. The maximum measured temperature of the fluid retrieved was 224°F (106.7°C).

Bridge plugs were placed in the 7-inch (177.8 mm) production casing to isolate the next two stages. A 20 ft (6.096 m) perforating gun, with six shots per ft at 60° phasing was used to perforate the casing. Because of the high temperatures, a drill rig was used to deploy and retrieve the plugs and gun. The locations in the cased sections of the well considered the number and orientation of the fractures observed in the image logs, and the need to avoid interference between stages. Locations in regions of the well containing high concentrations of NNE-SSW fractures (e.g. those parallel to the maximum horizontal stress direction) were considered to be particularly favorable for being stimulated at low pressures.

The second stage was slickwater pumped at rates up to 35 bpm (5.56 m^3/min). A total of 2,777 bbl (441.5 m^3) was pumped before the well was flowed back after being shut-in for 4 hours. Formation breakdown occurred at a pressure of 6,775 psi (46.7 MPa), which was much higher than the breakdown pressure observed during the first stage. The well was flowed back for 13 hours. A total of 1,478 bbl (235 m^3) (53%) was recovered with a maximum measured temperature of 205°F [96.1°C].

The third stage fracturing treatment was designed with the same pump rate schedule as the second stage, but a crosslinked carboxymethyl hydroxypropyl guar (CMHPG) polymer fluid with microproppant (particle size distribution of 5 to 1.97E-04 to 7.9E-03 inch (200 microns) was injected instead of slickwater. The viscosified fluid was selected to determine if the increased viscosity would influence the produced fracture geometry. 3016 bbs (480 m^3) were pumped at rates up to 35 bpm (5.56 m^3/min). A formation breakdown pressure of 6,659 psi (45.9 MPa) was observed, similar to the breakdown pressure during the Stage 2. The well was flowed back for 15.5 hours after a 5-hour shut-in. A total of 1,627 bbl (259 m^3) (54%) was recovered with a maximum measured temperature of 202°F (94.4°C).

Each of the three stages was tagged with a different naphthalene sulfonate tracer to assess interactions between stages and connections between wells 16A(78)-32 and 16B(78)-32 (Jones, et al., 2023), No evidence of mixed fluids was detected until the bridge plugs were retrieved. We interpret this data to indicate mixing of the injected fluids did not occur near the well bore. However, we cannot rule out mixing of fluids at greater distances. Once well 16B(78)-32 is completed, an interwell flow test will be conducted by pumping water into well 16A(78)-32. Despite their relatively short residence times in the reservoir rock, the concentrations of most major and minor elements increased with flowback time, suggesting significant water-rock interactions had occurred (Jones, et al, 2023). In addition to determining the chemistry of any produced fluids, we will also analyze them for their tracer contents which may help assess possible fracture connections.

5. SEISMIC MONITORING

Seismic monitoring at the Utah FORGE site is an ongoing activity. (Pankow et al., 2019, 2020; Mesimeri et al., 2021; Rutledge et al., 2022). Figure 7 shows the locations of the permanently installed seismic network and the regional seismicity. Shallow boreholes <200 ft (<60.96 m) deep have been instrumented with broadband sensors to form two rings, one at 1.86 miles (3 km) and the second at 4.97 miles (8 km) from the center of the Utah FORGE site. This network was designed to track event migration, fluid movement and fracture stimulation from the point of injection. Deeper permanent sensors include a three-component geophone and accelerometer permanently installed into the bottom of well 68-32 at a depth of 923 ft (281.33 m), a Silixa fiber optic cable cemented in the annulus of the 5 ½ inch (1,676.4 mm) casing in well 78-32 to 3268 ft (996.1 m) and a second Silixa fiber optic cable cemented to a depth of 4000 ft (1219.2 m) in the annulus of the 7-inch (177.8 mm) casing in well 78B-32. A third cable was deployed in well 56-32 but broke at a shallow depth and is not monitored.. No tectonic events have been detected beneath the Utah FORGE site since monitoring began in 1981.

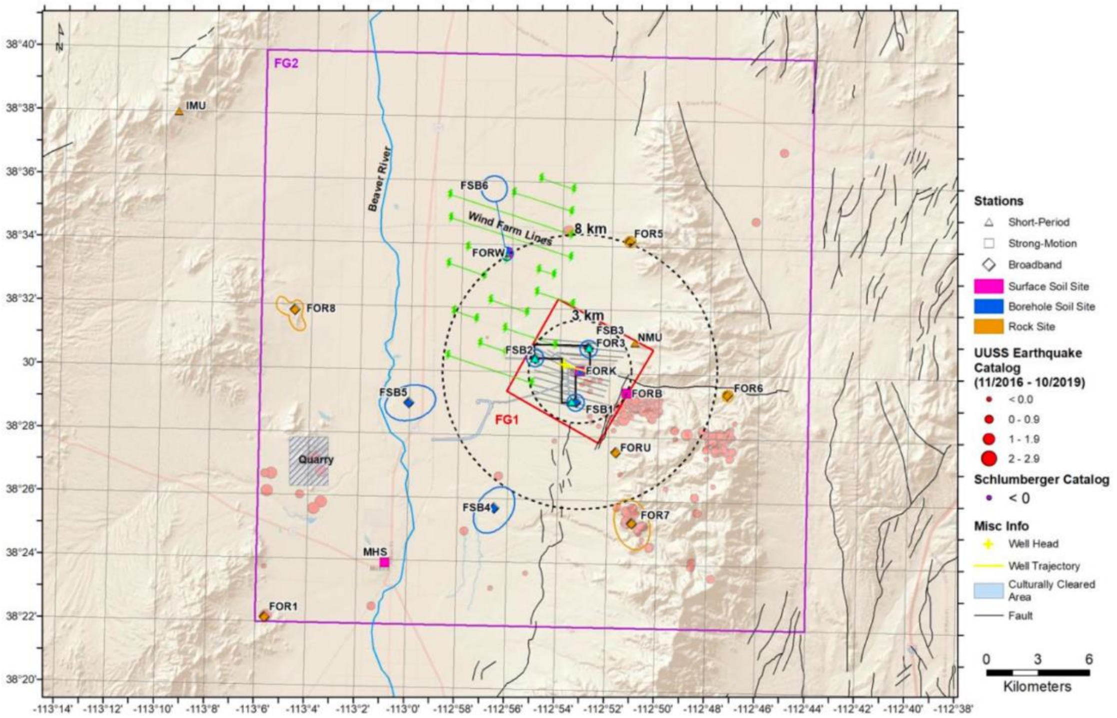

Figure 7: Map showing the locations of landmarks, seismic events and the monitoring network in the vicinity of the Utah FORGE site. The dotted circles are located approximately 1.86 miles (3 km) and 4.97 miles (8 km) from the center of well 58-32. The black polygon in the center of the figure shows the Utah FORGE footprint. Symbols: gray circles (size scaled by magnitude): earthquakes (1981-2016) from UUSS catalog; red circles (size scaled by magnitude): earthquakes (November 2016 – June 2021) from the University of Utah Seismic Stations catalog; yellow star: location of 1908 M 4.05 Milford earthquake; open and filled seismic stations: locations of seismic stations at 1.86 miles (3 km) and 4.97 miles (8 km); black lines: local mapped faults. Station MHS is located at Milford High School, indicating location of town. Quarry, airport, and Mineral Mountains indicate seismic cluster locations.

During the stimulation of well 16A(78)-32, the permanent monitoring network was augmented with geophone strings at reservoir depth in wells 56-32, 58-32, and 78B-32, a surface nodal array centered on the Utah FORGE site, a surface DAS cable, and a fiber optic cable incorporating 3-component geophones (Avalon's Boss tool). The DAS cable in well 78B-32 was also monitored at this time. A primary purpose of the monitoring was to provide direct, independent evidence of fracture height and width, information required for establishing the trajectory and depth of well 16B(78)-32.

Despite challenges due to the high temperatures that resulted in geophone failures, all three stages were monitored (Rutledge et al., 2021, 2022). More than 50,000 triggers were recorded with moment magnitudes (Mw) ranging from -2.3 to +0.5 M. For stage 1, 820 events were located and Mw were determined for an additional 2,527 (unlocated) events. For Stage 2, 1011 events were located and Mw were determined for an additional 4,614 (unlocated) events. For Stage 3, 1525 events were located and Mw were determined for an additional 16,942 (unlocated) events. Figure 8 displays the event locations in vertical and plan view, with the exception of low magnitude events formed early in Stage 1 near the 16A(78)-32 casing shoe. With time, Stage 1 events migrated upward close to the projected location of well 16B(78)-32 and then back to the 16A(78)-32 well course along the trajectory defined by the red and then white spheres. We suggest this trend reflects movement of the injected fluid along a natural fracture extending from the well bore. In contrast, the seismic events generated during Stages 2 and 3 moved away from the well bore as the stimulations progressed. The influence of preexisting fracture zones is also suggested by Stage 3 events, which follow two distinct trends at their upper end; one parallel to the maximum horizontal stress direction and the other defining a more northerly direction.

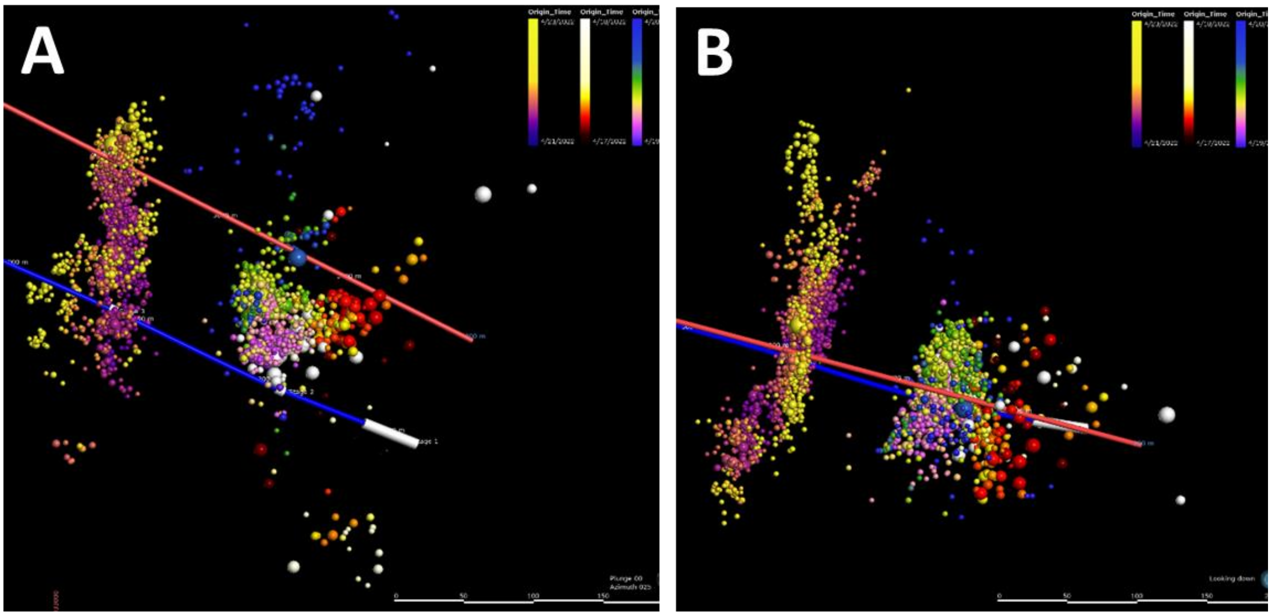

Figure 8: Locations of seismic events in vertical (A looking north) and plan (B looking to the northeast) views. The blue line is well 16A(78)-32. The open hole section of the well is colored white. The red line represents well 16B(78), located 328 .08 ft (100 m) above and parallel to well 16A(78)-32. Not shown are the numerous small events generated near well 16A(78)-32 during the Stage 1 stimulation. The color bar shows the chronology of the events with the earliest events denoted by the darker colors from the bottom of the color bar. The size of the spheres correlates with magnitude.

CONCLUSIONS

Utah FORGE is a unique field-scale laboratory for de-risking and testing new technologies for creating geothermal reservoirs where none exist naturally. The site is located in south-central Utah, within Mesozoic granitoid and high-grade Precambrian rocks.

The infrastructure currently consists of five vertical wells for tool testing and seismic monitoring, a long reach, highly deviated well for injecting water into the newly created fractured reservoir, and a permanent seismic monitoring network. During the recent stimulation of the injection well, 16A(78)-32, the network was augmented with a combined fiber optic/3 component geophone system, a surface nodal array, a surface DAS cable, and geophone strings deployed at reservoir depth in three wells.

In April 2022, three stages near the toe of well 16A(78)-32 were stimulated and monitored; one in the open hole section of the well and two behind casing. Injection rates of 50 bpm (7.95 m^3/min) in the 200 ft (60.96 m) of open hole and 35 bpm (5.56 m^3/min) in the cased section were achieved. Approximately 50% of the injectate was recovered. Seismic events ranging from -2.3 to +0.5 Mw were recorded.

The production well will be drilled parallel and 328.08 ft (100 m) above the injection well in 2023. Two DAS cables and a pressure-temperature tool will be cemented in the annulus of the 7 in (177.8 mm) production casing to locate where fractures connect the production and injection wells. In late 2023, the wells will be stimulated and long term interwell tests will be initiated.

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