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Current Activities at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE): A Laboratory for Characterizing, Creating and Sustaining Enhanced Geothermal Systems

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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 since the start of Phase 3 in October, 2020, covering drilling, geology, seismic monitoring, and communications and outreach.

Notable recent achievements include the drilling of two new deep wells, 16A(78)-32, a highly deviated well for injecting water into the reservoir and 56-32, a vertical well for seismic monitoring. Well 16A(78-32) was drilled vertically to 6111 m (5938 ft) and then deviated 65^o before reaching a MD of 10987 ft (3349 m), a first of its kind for geothermal development. Optimization of drilling parameters based on evaluation of Mechanical Specific Energy (MSE) and the use of PDC bits resulted in both wells being completed significantly ahead of schedule. The basement rocks encountered in both wells are dominated by granite and quartz monzonite, capped by variably sheared rhyolite at shallow levels and banded gneiss at deeper levels. The

FMI and UBI fracture image logs indicate an abundance of subparallel and subvertical fracture sets striking N-S to N25E, which are coherent with the modern stress regime.

The seismic monitoring network centers on a concentric two-ring array of permanent surface stations and borehole sensors comprising broadband instruments, motion sensors, a fiber optic cable, and a three-component geophone. During stimulations, the network will be augmented with geophone strings in the deep vertical wells and a nodal array.

1. Introduction

Enhanced Geothermal Systems (EGS) offer the potential of bringing 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 U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE) program was initiated to develop and test techniques 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.

The FORGE program is being conducted in three phases. Phase 1 involved desktop studies of existing data from five sites within the US. In 2018, the University of Utah's Milford, Utah site was selected as the site for the FORGE laboratory. During Phase 2, well 58-32 was drilled to a total depth of 2297 m (7536 ft). Injection testing has been performed on three zones in this well. The well encountered low permeability crystalline rocks at 961 m (3154 ft), and a bottom hole temperature of 199^{o}C (390°F). Two additional wells, 78-32 drilled to 998 m (3274 ft) and 68-32, drilled 303 m (994 ft) were completed as seismic monitoring holes.

Phase 3, which began in October, 2020, involves full implementation of the Utah FORGE laboratory, including completion of all infrastructure required to support drilling, stimulation, flow testing, and reservoir analysis. This paper provides an overview of the recent drilling results, geology, the seismic monitoring network, and communications and outreach.

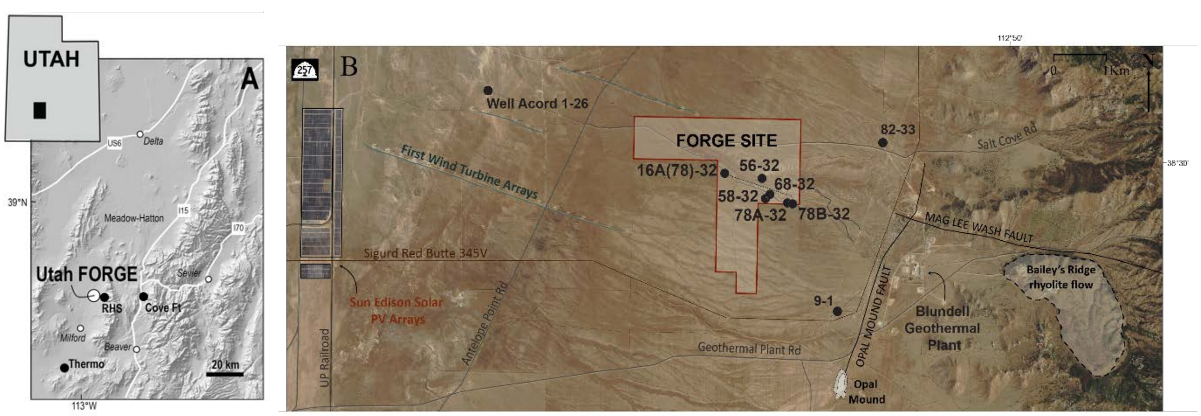

Figure 1: Location maps of the FORGE site. A) Map of southwest Utah. B) Expanded view of the area immediately surrounding the FORGE site.

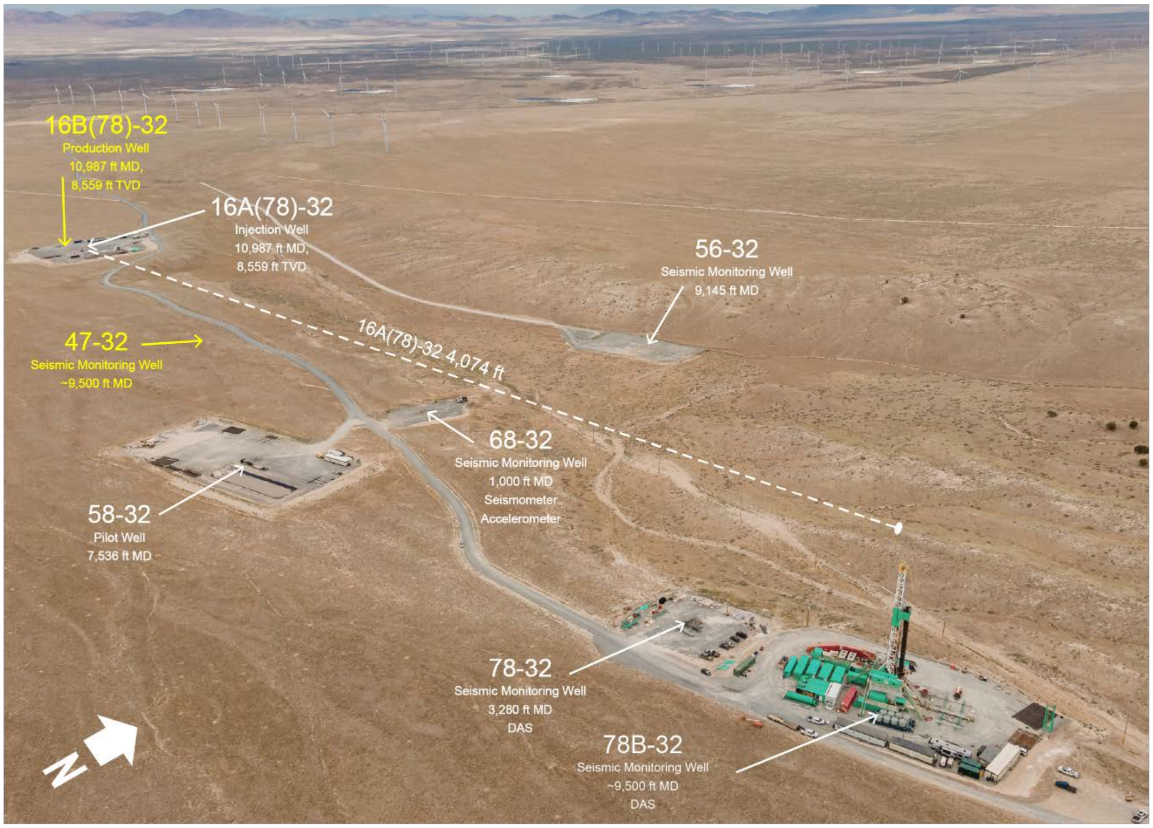

Figure 2. Aerial photo looking northwest across the Utah FORGE site showing the trajectory of 16A(78)-32 and the locations of drill pads for wells to be used for seismic monitoring and additional tool testing.

2. The Utah FORGE Site

The Utah FORGE site (Figures 1 and 2) is located ~322 km (200 miles) south of Salt Lake City and 16 km (10 miles) north of Milford, a small community with a population of 1700 (Fig. 1). The FORGE site is unpopulated and covers an area of about 5 km^2 (2 sq $miles^2$). 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 36 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 approximately the same distance south of Milford. An extensive road system provides access to the site.

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. An overview of the geoscientific attributes of the project are reported in Allis and Moore (2019), and the geology is shown in plan and cross-sectional views in Figure 3.

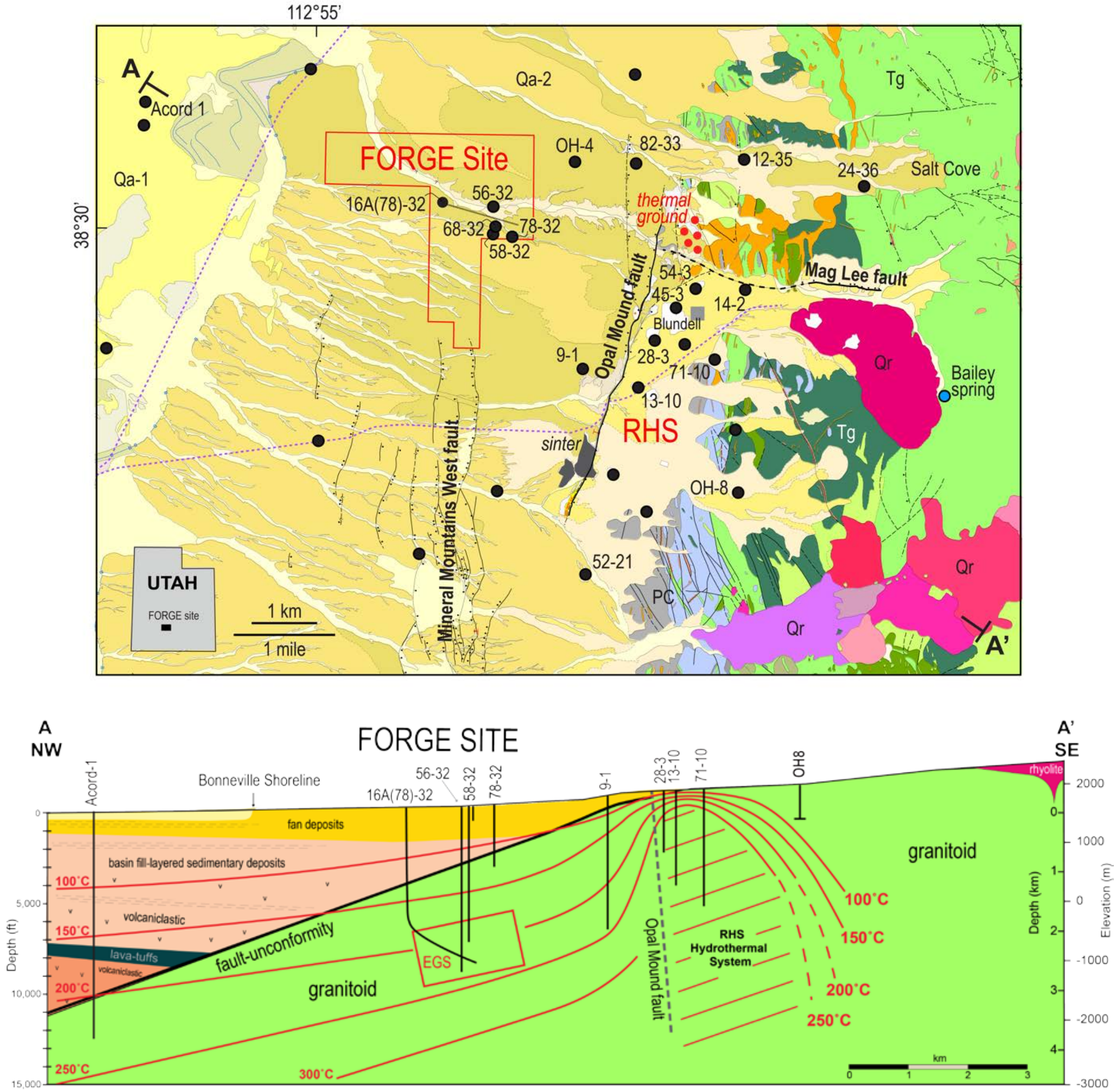

Figure 3. A) Geologic map of the Utah FORGE site and surrounding area (modified from Nielson et al. 1986 and Kirby, 2019), For clarity, only a few of the many wells are shown. Abbreviations: Qa-1=Lake Bonneville silts and sands; Qa-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoid; PC=Precambrian gneiss; black filled circles=wells. B) Northwest-southeast section showing the 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.

3. Drilling results

Since late 2020, two new deep wells have been completed, and a third was spudded in late June, 2021. The centerpiece of the laboratory will be a pair of highly deviated wells. Well 16A(78)-32, the first of these two wells drilled, will be used to inject water into the reservoir. The well was completed in January, 2021 (Figures 2 and 4). Well 16A(78)-32 was drilled vertically through approximately 1082 m (3550 ft) of basin fill sediment before penetrating into high strength, crystalline basement. At 1810 m (5938 ft) the well was deviated to obtain an inclination of 65° from the vertical. Drilling continued to a measured depth of 3349 m (10,987 ft). The true vertical depth is 2609 m (8,559 ft). The well was completed with 7-inch casing to approximately 61 m (200 ft) of total depth. Core was obtained from two intervals; the first starting at around 1,676 m (5500 ft) depth and the second at around 3339 m (10955 ft). Seventy-four feet (23 m) of granitoid and metamorphic rocks were retrieved. Temperature surveys in nearby well 56-32 suggest the bottom hole temperature will be close to 220°C (428°F). To our knowledge, this is the first time a large diameter highly deviated well has been drilled for geothermal purposes.

A short-term stimulation test to measure stress in the open hole section of well 16A(32)-78 was conducted shortly after the well was completed. The results indicate a closure stress gradient of 0.71-0.75 psi/ft and very low permeability of 21 micro-Darcies, which are consistent with earlier results (Forbes et al., 2019; Xing et al. 2021). Further stimulation testing is planned for late 2021. Two of the stimulation intervals will be conducted in the cased portion of the well.

The second new well 56-32 was drilled vertically to 2,787 m (9,145 ft) and completed with 5 ½ inch casing to 2,775 m (9,105 ft). This well is to be used primarily for deployment of geophone strings and seismic monitoring. Unfortunately, a Silixa multi-mode fiber optic cable outside the casing, was broken during a cementing operation. Attempts to obtain sidewall cores from the lower half of the well in lieu of large diameter core were not successful.

The resounding success story of the drilling is that both wells were completed significantly ahead of schedule (Figure 4). During the drilling of 56-32, a new record for a single bit run of 1208 ft in 53 hours at an average rate of penetration of 25.4 ft/hr achieved. The ability to repeat highly efficient drilling performance in both wells is attributed to the use of PDC bits manufactured by Reed-Hycalog bits 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).

4. Geology

Utah FORGE is located on young alluvial fan deposits which make up the near surface stratigraphy of basin fill strata (>2000 ft thick) infilling the North Milford valley. The underlying crystalline basement that will host the EGS reservoir is dominated by Tertiary plutonic rocks comprising granite and quartz monzonite, accompanied by granodiorite, quartz monzodiorite, and diorite (Jones et al., 2019). These granitoids form the core of the Mineral Mountains and range in age from 26 to 8 Ma (Aleinikoff et al., 1987; Coleman and Walker, 1992; Coleman et al., 2001). 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), whereas the oldest rocks are made of tightly folded gneiss that is engulfed by granitoids (Nielson et al., 1986; Kirby, 2019).

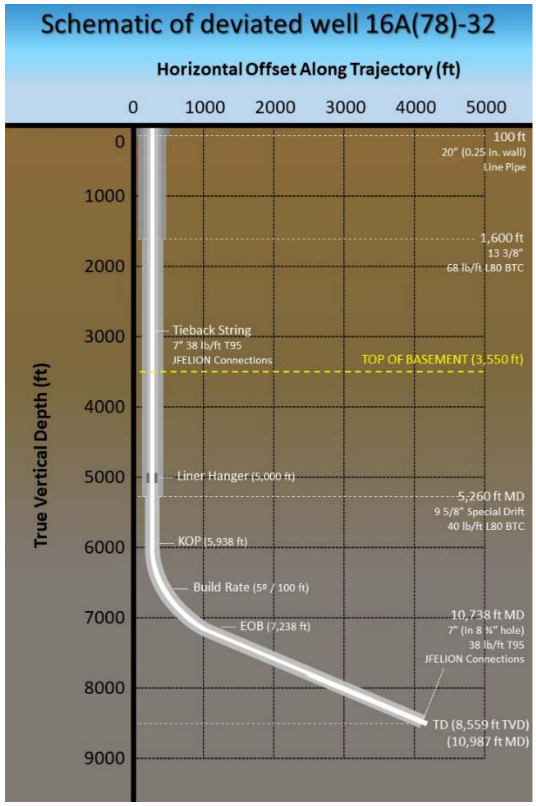

Figure 4. Details of well 16A(78) showing the casing program and distribution of rock types. See figure 1 for the location of the wellhead and trajectory of the lateral.

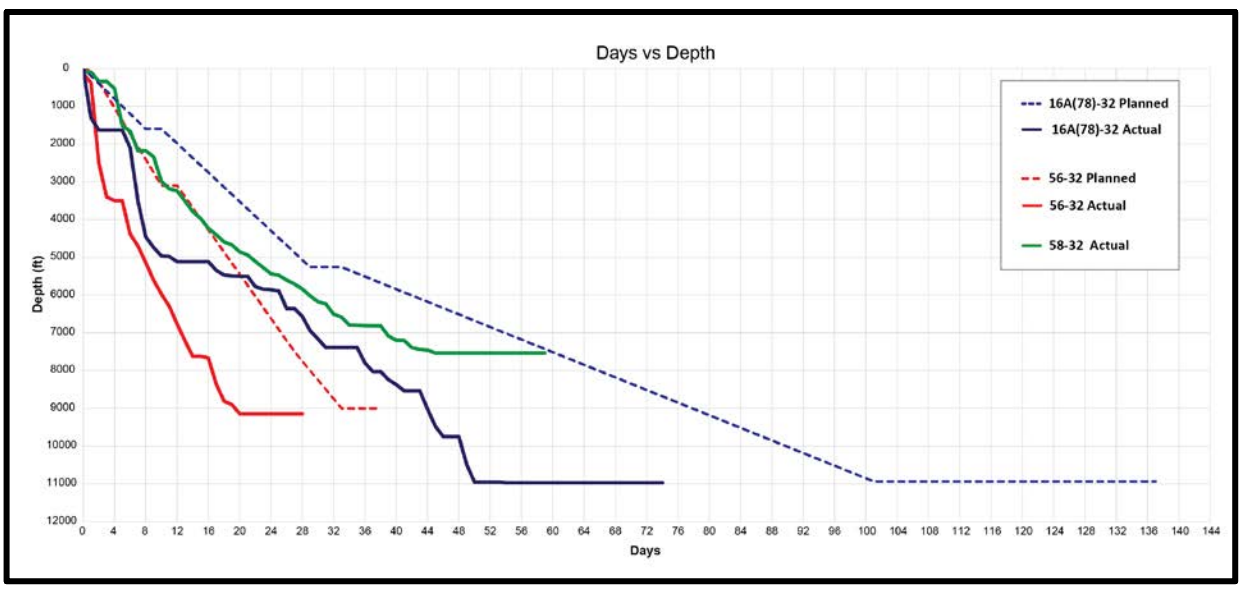

Figure 5. Comparison of drilling of planned and actual drilling progress for wells 16A(78)-32 and 56-32 as a function of schedule and depth.

The known faults in the vicinity of Utah FORGE are products of Basin and Range extension, mostly forming in late Miocene time after the main phase of plutonic intrusion (Coleman et al., 2001; Bartley, 2019). Analysis of outcrops, seismic reflection, and correlation of drill logs indicates the existence of four major structures (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, whereas the Mineral Mountains West fault system represents a corridor of north-south trending fault scarps (<5 m high) in fan deposits extending south of Utah FORGE. The most significant fault remains unnamed, and it forms a gently undulating ramp dipping 20-35° west. The fault occurs at the contact between the underlying basement rock and the onlapping basin fill (Figure 3). This and related subparallel structures in the basement are believed to have originated as steeply dipping faults that 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).

The geological and geophysical logs from wells 16A(78)-32 and 56-32 are being used to build on earlier reports (e.g., Jones et al., 2019; Forbes et al., 2019) that improve understanding about the reservoir characteristics. While the data are still being processed and analyzed, some provisional results are available. From thin section petrography and X-Ray Diffraction analysis, the basement rocks are dominated by granite and quartz monzonite capped by sheared rhyolite and interfinger with narrow zones of banded gneiss at depth (Figure 6). Analysis of FMI and UBI fracture image logs shows there is an abundance of subparallel and subvertical N-S to N25E fractures , which are coherent with the modern stress regime. The new geological data have also been used to make slight revisions to the location of the basement contact in the earth model.

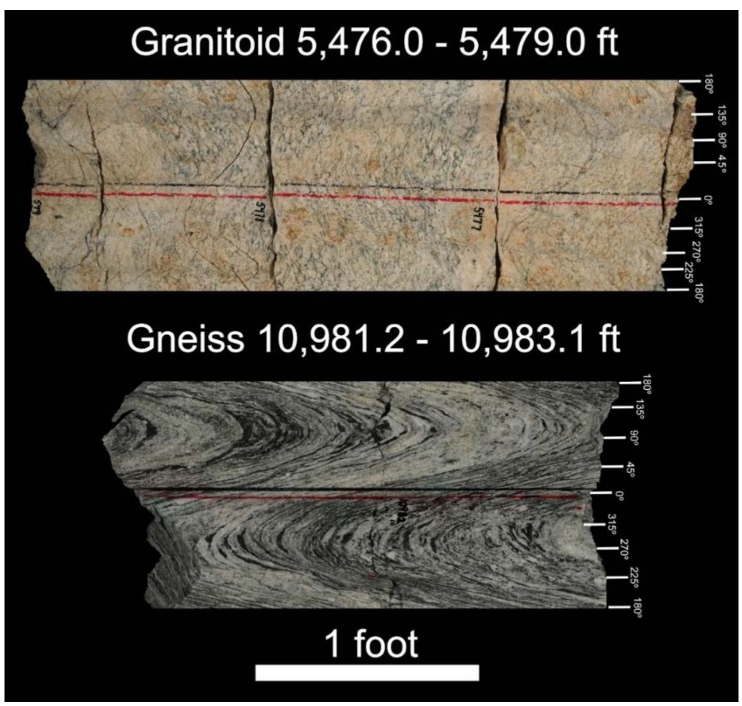

Figure 6. Stitched photos that give a 360° view of the cylindrical exterior of two core samples from well 16A(78)-32. The upper core interval is a sample of the granitoid, and the lower core interval is a sample of the tightly folded banded gneiss.

The regional geoscientific understanding is being updated as interpretation and analysis of the magneto-telluric data and groundwater chemistry progress. These two independent lines of study are revealing the deep-seated controls on heat and mass transfer and the origins of geothermal resources. A recent report on production fluids from geothermal field at Roosevelt Hot Springs shows evidence for modest but measurable long-term EGS heat mining (Simmons et al., 2021).

5. Seismic Monitoring

Seismic monitoring at the Utah FORGE site has two main goals: 1) capturing events at an M_{comp} level of 0 in order to monitor seismic hazard and inform a traffic light system for risk mitigation; and 2) monitoring fracture growth in the reservoir during stimulation and circulation of water to an M_{comp} -2. To achieve these goals, a state-of-the-art seismic network is being installed, comprising of permanent surface stations and borehole sensors (geophones and fiber optic cables) and temporary nodal arrays and geophone strings. Several publications describe the natural and induced seismicity detected through 2020 (Pankow et al., 2019, 2020; Lelouche et al 2020a, 2020b; Mesimeri et al., 2021). No events other than the microseismicity during stimulation testing have so far been detected beneath the Utah FORGE site.

The permanent network shown in Figure 7, currently comprises six surface stations made up of four broadband instruments, one short period sensor and one ground motion sensor that is located at the Blundell geothermal field. Three shallow postholes (<61 m (<200 ft) deep have been instrumented with broadband sensors to form a 3 km (1.7 miles) inner ring of detectors that is designed to resolve the depths of individual events for improved hypocentral control of induced microseismicity and record any runaway fractures. A second ring at 8 km (5.0 miles)is designed to resolve the horizontal locations of individual events for improved epicentral control of induced microseismicity. The ring will contain four new postholes expected to be deployed before the stimulation campaign begins later in 2021. In combination, the inner and outer rings of sensors will improve capability to track event migration, fluid movement and fracture stimulation from the point of injection. Deeper permanent sensors include a three-component geophone and a three-component accelerometer that are permanently installed into the bottom of well 68-32, and a Silixa fiber optic cable cemented in the annulus of the 5 ½” casing in 78-32 to 996 m (3268 ft). A second Silixa fiber optic cable will be deployed in well 78B-32.

The temporary network comprises geophone strings that will be lowered into wells (56-32, 58-32, 78-32, 78B-32) during stimulation experiments, and an array of nodal instruments that will be deployed for periods of about one-month covering scheduled phases of stimulation.

6. Communications and Outreach

The Communications and Outreach program provides up to date information about Utah FORGE progress and activities and educational materials. The program serves a broad spectrum of stakeholder interests, including surrounding landowners and Beaver county residents, K-12 through to university-level students and teachers, elected officials (local, state, federal), and the R&D community. A range of internet/social media platforms are utilized, and links to these can be reached from the dedicated website (https://utahforge.com/outreach/). A quarterly update is published in the e-newsletter “At the CORE”, and regular features on the website include “Word of the Week” and “Did You Know”, which aim to improve geothermal literacy. Supplementary materials comprise links to podcasts, webinars, K-12 lesson plans, and modules. Despite the pandemic, quarterly site visits have been carried out to keep the local community informed about drilling, stimulation and induced seismicity. Vigorous effort is undertaken to keep public officials informed through ad hoc meetings on the site, at the State Capitol in Salt Lake City, and via teleconferences. In addition to a full-time communications specialist, Utah FORGE employs University of Utah students. These include interns who generate content and graphical materials, a graduate student specializing in K-12 education, and chemical engineering students who build modules for classroom demonstration. In fall 2020, an undergraduate level capstone class in Communications developed a public survey to assess general knowledge about geothermal energy in the populations of western States; the results will be posted to GDR (Geothermal Data Repository hosted by NREL) and follow-up surveys are planned to provide a longitudinal dataset of public perceptions.

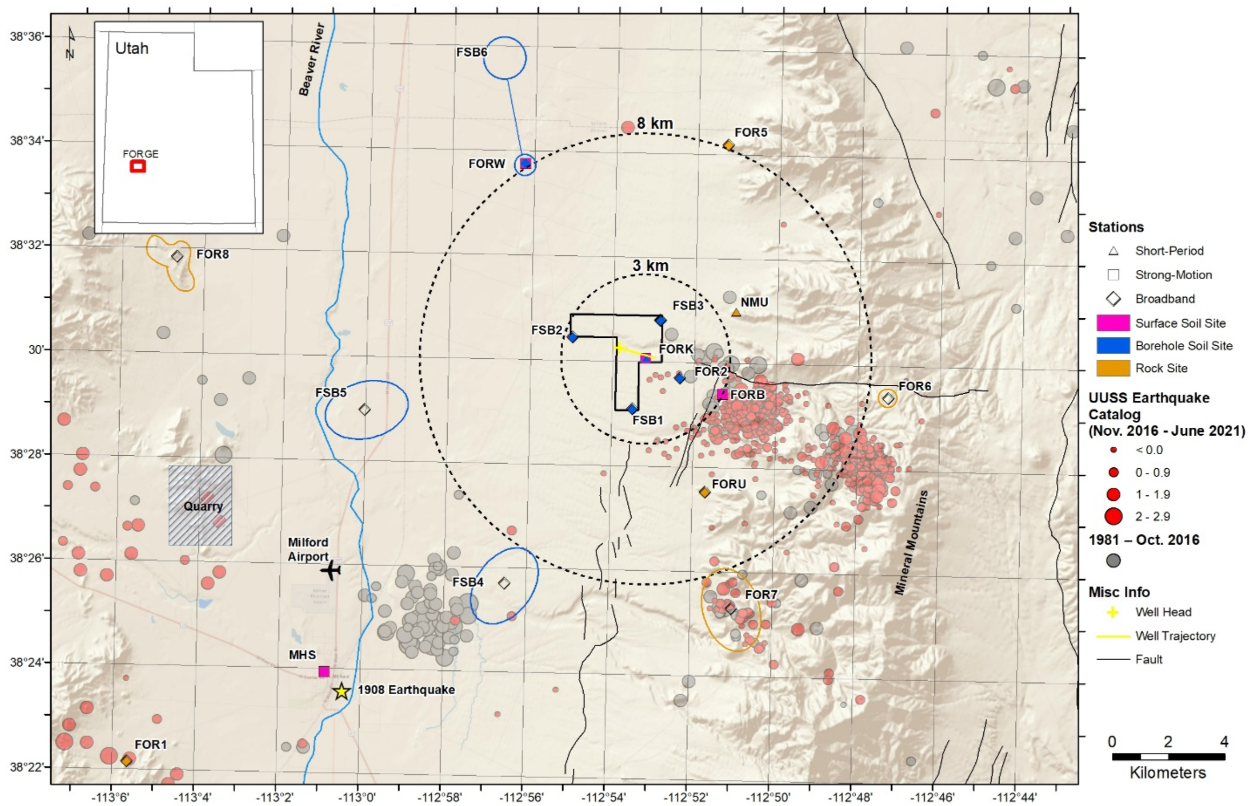

Figure 7. Locations of microseismic events and the monitoring network in the vicinity of the Utah FORGE site. The dotted circles are located approximately 3 km (1.7 miles) and 8 km (5 miles) from the center of well 58-32. The black polygon of the main figure shows the FORGE footprint. Symbols: gray circles (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; filled seismic stations: installed as of July 2021; open symbols with ellipsoids: general location of stations to be installed in late 2021; 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.

7. Looking Forward

The paper provides only a snapshot of some of the various current activities at Utah FORGE. In the fall of 2021, the first campaign of reservoir stimulation in 16A(78)-32 is scheduled to be performed. The R&D program involving outside research teams has commenced, and the projects cover a range of topics, including tool development, estimating reservoir stress parameters, characterization of thermal-hydrological-mechanical-chemical effects due to stimulation, stimulation methods, and integrated laboratory-modeling studies. A high priority for achievement in the near future is an improved level of reliable performance at reservoir temperatures (i.e., 225°C (440°F) for the tools used in zonal isolation, seismic monitoring and reservoir characterization.

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